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Structure Specified Optimal Robust H_∞ Loop Shaping Control of Multivariable Electro-Hydraulic Servo System using GA and PSO

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ABSTRACT: A structure specified robust controller based on H_∞ loop shaping control is proposed in this paper. It can be used to ensure the robust performance under a fixed structure controller. In this proposed technique, Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) are applied for the optimal controller design, and the inverse of infinity norm from disturbances to states which is called as the stability margin is formulated as the objective function for finding the optimal controller. Simulation results of MIMO electro-hydraulic servo system show that the proposed controller has quite simpler structure and less order than that of the conventional H_∞ loop shaping controller and its stability margin is approximately near the H_∞ loop shaping controllers.

KEYWORDS: H_∞ loop shaping, fixed structure, MIMO electro-hydraulic servo system, Genetic Algorithm, Particle Swarm Optimization.

I. INTRODUCTION

The Electro-hydraulic servo systems are well known for their fast dynamic response, high power to inertia ratio, and control accuracy. That is why, Electro-hydraulic actuator is an attractive choice for being used in both industrial and non-industrial applications. These systems are highly non-linear in nature due to which their controlling is very important. If the system dynamics can be precisely described and the plant dynamics vary in the vicinity of the designed operation point, a fixed parameter controller may be designed using conventional control theory to acquire the desired output.

However, for most of the industrial systems, it is quite difficult to describe the system precisely. In addition, due to disturbances, uncertainties, variations of loads, and changing process dynamics, the system parameters may vary. Traditional linear control techniques based on small perturbation theory can deal with a system operated in the vicinity of the designed working state, which may lead to degradation in the performance of a system under varying parameter conditions. However, the robust controllers are difficult to implement for practical applications. The simple controller such as PI, PID controller is today's most commonly used control in servo systems. This problem extends the gap between the theoretical and practical approaches.

The design of a structure specified robust controller has been proposed to solve this problem and has become an interesting area of research because of its simple structure and practicable controller order which is very low. B.S. Chen. et. al. [1] proposed a PID design algorithm for mixed H_2/H_∞ control. In their paper, PID control parameters were tuned to achieve mixed H_2/ H_∞ optimal control in the stability domain. Almost similar idea was proposed in [2] by using the intelligent genetic algorithm to solve the mixed H_2/H_∞ optimal control problem. In their paper, H_2 is mixed with H_∞ to indicate both the performance and robustness of entire system. In addition, the controller parameters were tuned in the stability domain evaluated by Routh-Hurwitz stability criterion and sampling technique. In [3], a robust H_∞ optimal control problem was solved by using a structure specified controller with Genetic Algorithm (GA). Mixed sensitivity approach was adopted for indicating the performance of designed controller. From [3], GA is a feasible method to design a fixed-structure H_∞ optimal controller. However, the fixed structure controller based on H_∞

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optimal control designed in [1-3] proves difficult for both the uncertainty of the model and the performance are essentially chosen weights.

Alternatively, McFarlane and Glover [4] proposed an alternative technique called H_∞ loop shaping control to design a robust controller. This technique is based on the concept of loop shaping which is easy for selecting the weighting function as they requires only two specified weights, pre- and post-compensator weights [4], for shaping the nominal plant so that the desired open loop shape is achieved. H_∞ loop shaping controller having fixed structure is proposed by [4-6]. A. Umut Genc in 2000 [5] used the concept of state space approach and BMI optimization. As shown in this research work, specifying the initial solution has a huge effect on the final optimal solution because of the local minima problem. S. Patra *et.al.* in [6] designs an output feedback robust controller that has the same structure as the pre-compensator weight which is normally designed as PI.

However, the resulting controller in [5-6] is always ineffective as the problem of local minima often occurs in the design. Optimization algorithms such as genetic algorithm, particle swarm optimization technique, simulated annealing, etc., can be employed to solve these problems. In this paper, a new design technique by the GA and PSO based structure specified robust H_∞ loop shaping control is proposed for MIMO Electro-hydraulic servo system. GA and PSO are employed to find the optimized parameters of the controllers. The structure of controller is selectable here and the fixed-structure robust PI controller is designed. Simulation results show that the controller designed by the proposed approach has a good performance and robustness properties as well as a simple structure of low order.

The remainder of this paper is organized as follows. Section II represents the modelling of MIMO Electro-hydraulic Servo system. In Section III, conventional H_∞ loop shaping and the proposed technique are illustrated along with the GA and PSO algorithms. The design examples and results along with the comparison between GA and PSO results are described in section IV. Finally, Section V concludes the paper.

II. ELECTRO-HYDRAULIC SERVO SYSTEM

The overall electro-hydraulic servo system consists of power supply components (pumps), control segments (servo valves), and executive components (actuators). The two actuators are controlled by two separate electro-hydraulic servo systems as shown in Fig.1. One is a position control system which is used to control the actuator movement and the other is a force control system which is used to supply a required force to the system load. The actuators of the two systems are disconnected to form two independent control systems.

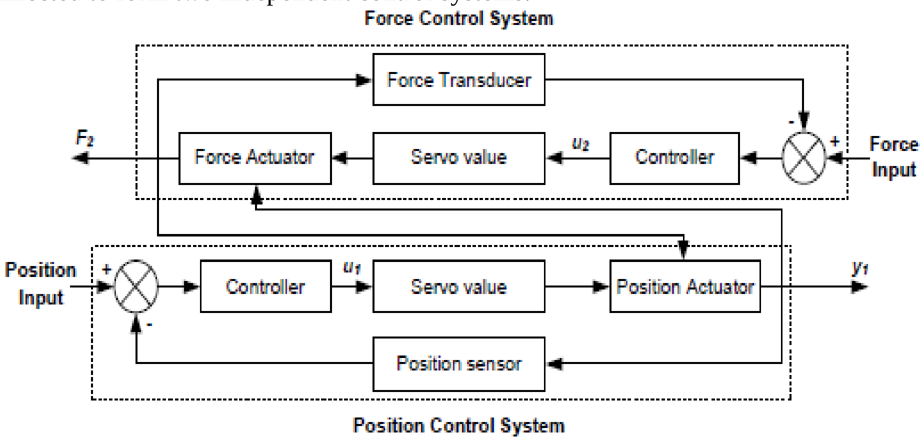

Fig.1. MIMO Electro-hydraulic Servo System

It is clear from Fig.1 that the position control system and the force control system are coupled. This coupling results in external disturbances to each system. The motion of the position actuator results in a motion disturbance input to the force control system, and the force generated by the force control system causes a force disturbance input to the position control system. In addition, the overall system is a highly nonlinear system with time varying parameters and

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other unknown disturbances.

The objective of the electro-hydraulic servo system is to satisfy the requirements such as zero steady state errors in motion of the actuator and force output. The state-space of the MIMO electro-hydraulic servo system is given as:

$$\dot{x} = Ax + Bu$$
$$y = Cx$$

The state vector of this plant consists of the four variables which are supply pressure in force control system, supply pressure in position control system, position of the actuator and velocity of the actuator. The dynamic model of this system is an MIMO system which has 2 outputs (y), $F2$ – force of the system and $y1$ – position of the actuator, and 2 inputs (u), $u1$ – input servo value of the position control system, and $u2$ – input servo value of the force control system.

III. CONVENTIONAL H_∞ LOOP SHAPING CONTROL AND PROPOSED TECHNIQUE

A. Conventional H_∞ Loop Shaping Control

To design a robust controller, H_∞ loop shaping control is an efficient method. An alternative way to represent the model uncertainty is introduced. The uncertainty is described by the perturbations directly on the co-prime factors of the nominal model. The H_∞ robust stabilization against such perturbations and the consequently developed design method, the H_∞ loop-shaping design procedure (LSDP) could relax the restrictions on the number of right-half plane poles and produce no pole-zero cancellations between the nominal model and controller designed. The method does not require an iterative procedure to obtain an optimal solution. The H_∞ LSDP inherits classical loop-shaping design ideas.

The essential elements of this approach are two weighting functions W_1 (pre- compensator) and W_2 (post-compensator) for shaping the original plant G_o so that desired open loop shape in frequency domain is achieved. In this technique, normalized numerator N_s and denominator M_s factors are the separated parts of shaped plant G_s.

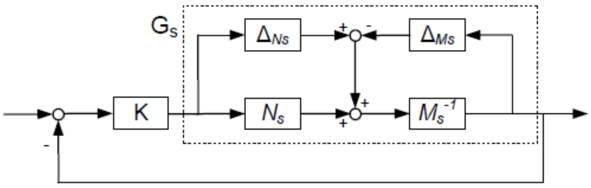

Fig.2. Co-prime factor robust stabilization problem

Consequently, the shaped plant can be written as:

$$G_S = W_2 G_0 W_1 = N_S M_S^{-1}$$
$$G_S = (N_S + \Delta_{NS})(M_S + \Delta_{MS})^{-1}$$

where Δ_{Ns} and Δ_{Ms} are the uncertainty transfer functions in the nominator and denominator factors, respectively. $\|\Delta_{Ns}, \Delta_{Ms}\|_\infty \le \varepsilon$, where ε is the stability margin. The determination of the normalized co-prime and the solving of the H_∞ loop shaping control can be seen from [8].

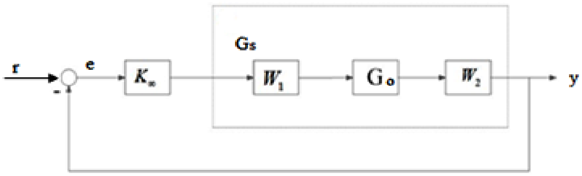

Fig.3. Block diagram of H_∞ loop shaping control

In this approach, the pre-compensator (W_1) and post- compensator (W_2) weights for achieving the desired loop are defined, then optimal stability margin (ε_{opt}) is solved by the following equation:

$$\gamma_{opt} = \epsilon_{opt}^{-1} = \left\| \begin{bmatrix} I \\ K \end{bmatrix} (I + G_s K)^{-1} M_s^{-1} \right\|_\infty$$

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If the (ε_{opt}) is very small, then go back to select new weighting function. Select the stability margin ($\varepsilon<\varepsilon_{opt}$) and then synthesize the controller, $K\infty$, by solving the following inequality:

$$\|T_{ZW}\|_\infty = \left\|\begin{bmatrix} I \\ K_\infty \end{bmatrix}(I+G_SK_\infty)^{-1}M_S^{-1}\right\| = \left\|\begin{bmatrix} I \\ K_\infty \end{bmatrix}(I+G_SK_\infty)^{-1}[I \quad G_S]\right\|$$

The final feedback controller (K) is:

$$K = W_1 K_\infty W_2$$

B. Proposed technique

The proposed technique starts with assuming the structure of the controller ($K(p)$). The parameter, p, of this controller is variable. This parameter, p, consists of following vector: Then, GA and PSO are used to find the optimal parameter, p. In robust problems, the stability margin (ε) is the single index to check the performance and stability of the designed controller which is obtained as follows.

$$\|T_{ZW}\|_\infty^{-1} = \epsilon = \left\|\begin{bmatrix} I \\ K \end{bmatrix}(I+G_SK_\infty)^{-1}[I \quad G_S]\right\|_\infty^{-1}$$

where K_∞ can be found by $K_\infty = W_1^{-1}K(p)W_2^{-1}$. Suppose that W_1 and W_2 can be inversed. Generally, W_2 is chosen to be equal to identity matrix I. Therefore, objective function can be written in this form:

$$\|T_{ZW}\|_\infty^{-1} = \varepsilon = \left\|\begin{bmatrix} I \\ W_1^{-1}K(p) \end{bmatrix}(I-G_SW_1^{-1}K(p))^{-1}[I \quad G_S]\right\|^{-1}$$

For this design of controller, the controller $K(p)$ will be designed to minimize the infinity norm from disturbance to state or maximize stability margin by GA and PSO method.

C. Genetic Algorithm

The genetic algorithm (GA) is an optimization technique that performs a parallel, stochastic and directed search to evolve the fittest (best) solution. GA is different from conventional optimization methods as it employs the principles of evolution, natural selection and mutation and maximizes the mean fitness of its population through the iterative application of the genetic operators.

Three main operators that comprise GA are reproduction, crossover, and mutation.

The genetic algorithm follows the following steps:

Step1: Generate an initial population of binary string.

Step2: Calculate fitness value of each member of population based on the problem type (minimization or maximization).

Step3: Generate offspring string through reproduction, crossover and mutation and evaluate.

Step4: Calculate fitness value for each string.

Step5: Terminate the process if required solution is obtained or number of generation is attained.

D. Particle Swarm Optimization

PSO technique conducts search using a population of particles, corresponding to individuals. Each particle represents a candidate solution to the problem at hand. In a PSO system, particles change their positions by flying around in a multidimensional search space until computational limitations are exceeded.

In PSO, the population dynamics simulates a 'bird flock's' behavior, where social sharing of information takes place and individuals can profit from the discoveries and previous experience of all the other companions during the search for food. Thus, each companion, called particle, in the population, which is called swarm, is assumed to 'fly' over the search space in order to find promising regions of the landscape.

In this, each particle is treated as a point in a d-dimensional space, which adjusts its own 'flying' according to its flying experience as well as the flying experience of other particles (companions). In PSO, a particle is defined as a moving point in hyperspace. For each particle, at the current time step, a record is kept of the position, velocity, and the best position found in the search space so far. The PSO algorithm is as follows:

Input: Randomly initialized position and velocity of the particles: $X_i(0)$ and $V_i(0)$

Output: Position of the approximate global optima X(0)

Begin

While terminating condition is not reached **do**

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Begin
For i = 1 to number of particles
Evaluate the fitness= $f(X_i)$;
Adapt velocity of the particle;
Update the position of the particle;
increase i;
end

IV. SIMULATION RESULTS AND DISCUSSION

The state-space representation of the nominal plant has been taken from [7] and is given as:

$$A=\begin{bmatrix}65.58 & 59.98 & 18.02 & 14.15\\ 25.98 & 121.5 & 0 & 25.98\\ 12.45 & 12.38 & 84.65 & 0\\ 0.99 & 0.91 & 21.53 & 61.52\end{bmatrix}, B=\begin{bmatrix}17.79 & 0\\ 158.1 & 0.13\\ 4.68 & 79.8\\ 0 & 0\end{bmatrix}$$

$$C=\begin{bmatrix}0 & 1.07 & 0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}, D=\begin{bmatrix}0 & 0\\ 0 & 0\end{bmatrix}$$

In this paper, the pre- and post-compensator weights are selected as:

$$W_1=\begin{bmatrix}\frac{0.8s+60}{s+0.001} & 0\\ 0 & \frac{0.8s+60}{s+0.001}\end{bmatrix}, W_2=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$$

The structure of controller is chosen as PI controller in the matrix form as follows:

$$K(p)=\begin{bmatrix}\frac{p_1 s+p_2}{s+0.001} & \frac{p_3 s+p_4}{s+0.001}\\ \frac{p_5 s+p_6}{s+0.001} & \frac{p_7 s+p_8}{s+0.001}\end{bmatrix}$$

The design vector to be obtained by solving optimization problem becomes $X=[p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8]$ and the objective function to be minimized is $\|T_{ZW}\|_\infty$.

A. Results using Genetic Algorithm

Firstly singular values of plant and shaped plant using pre and post compensator weights are plotted and then unit step is fed into position and force command to see the respective responses.

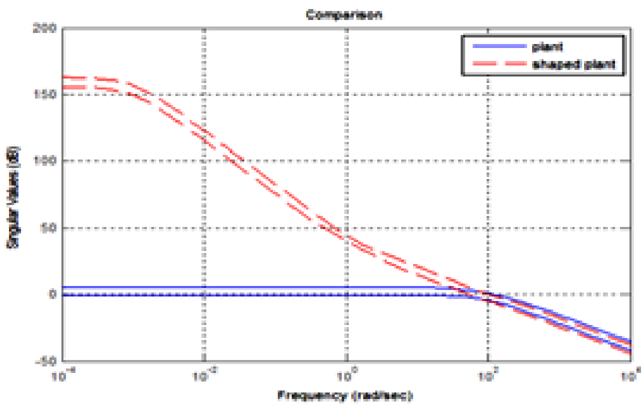

Fig.4. Singular values of plant and shaped plant using GA

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Singular values of Multivariable electro-hydraulic servo system and desired loop shape are plotted in Fig.4. It can be seen that the bandwidth and performance of plant are significantly improved by the pre- and post- compensator weights. The shaped plant obtained has large value of gains at low frequencies for performance and small value of gains at high frequencies for noise attenuation. Hence, the robust requirement is satisfied with these weighting functions.

The optimal solution obtained after running GA is as follows:

$$K(p) = \begin{bmatrix} \frac{-0.8s + 2.19}{s + 0.001} & \frac{0.11s + 1.27}{s + 0.001} \\ \frac{0.2s + 0.14}{s + 0.001} & \frac{-0.3s + 3.34}{s + 0.001} \end{bmatrix}$$

The optimal stability margin of the shaped plant is found to be 0.761using GA. This value indicates that the selected weights are compatible with robust stability requirement in the problem.

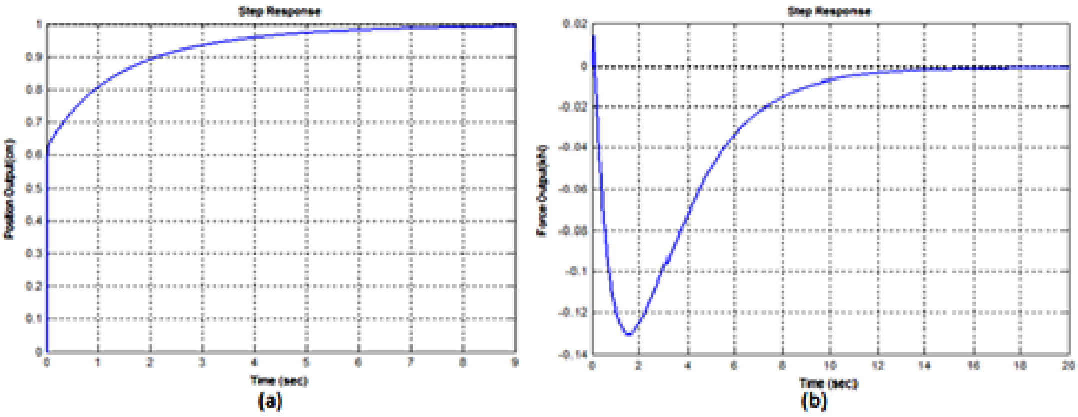

Fig.5. Position and Force of the system with unit step position command using GA

Fig.5 shows the response of the outputs of the servo system (Position and Force) with the unit step position command as input using GA.

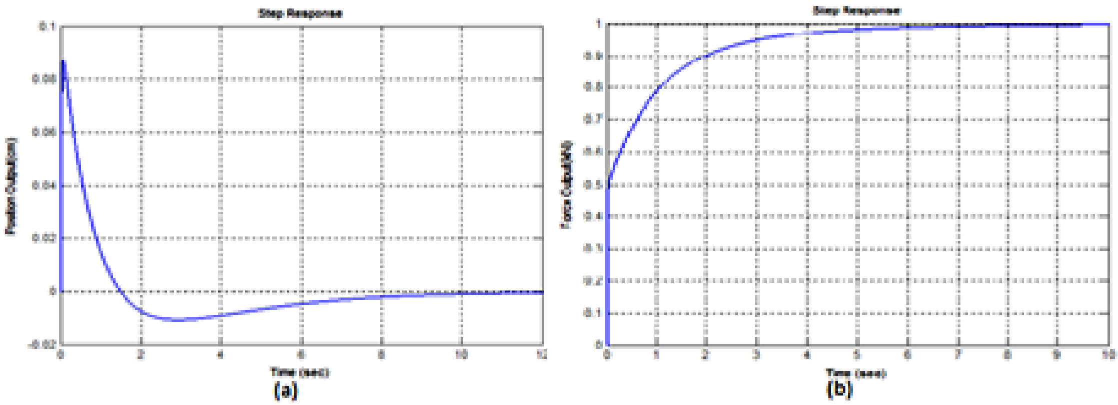

Fig.6. Position and Force of the system with unit step force command using GA

Fig.6 shows the response of the plant with the unit step force command using GA. It can be found that the proposed controller gives quite well performance.
It can also be noted from Figs.5 (b) and 6 (a) that this method proves to be suitable to reduce the couplings between position control and force control.

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B. Results using Particle Swarm Optimization

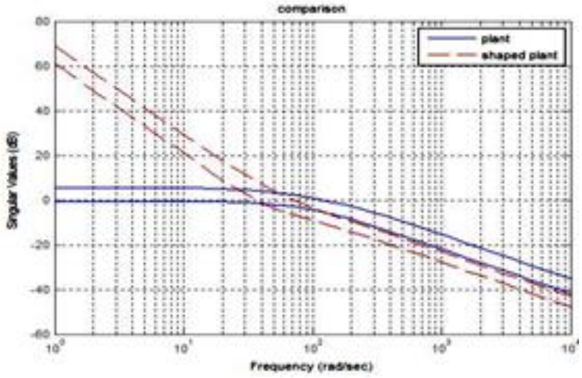

Fig.7. Singular values of plant and shaped plant using PSO

Singular values of Multivariable electro-hydraulic servo system and desired loop shape are plotted in Fig. 7.
The optimal solution obtained after running PSO is as follows:

$$K(p) = \begin{bmatrix} \frac{-0.45s + 17.68}{s + 0.001} & \frac{0.24s + 9.59}{s + 0.001} \\ \frac{-0.24s + 1.75}{s + 0.001} & \frac{-0.59s + 28.22}{s + 0.001} \end{bmatrix}$$

The optimal stability margin of the shaped plant is found to be 0.7801 using PSO. This value indicates that the selected weights are compatible with robust stability requirement in the problem.

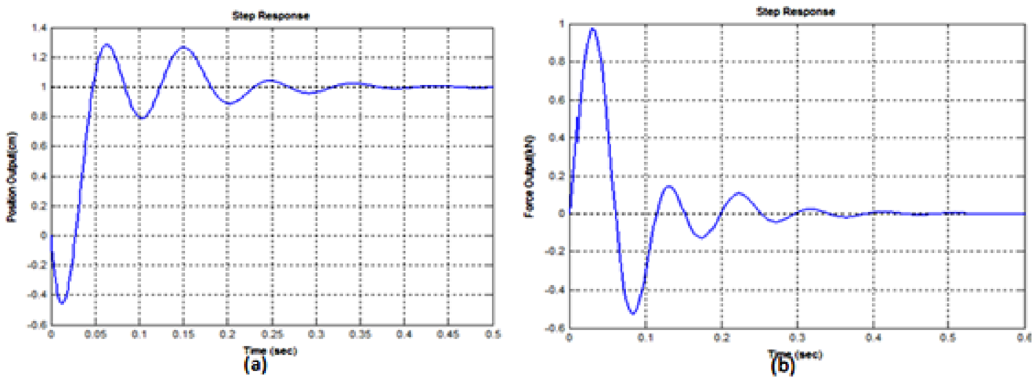

Fig.8. Position and Force of the system with unit step position command using PSO

Fig.8 shows the response of the outputs of the servo system (Position and Force) with the unit step position command as input using PSO.

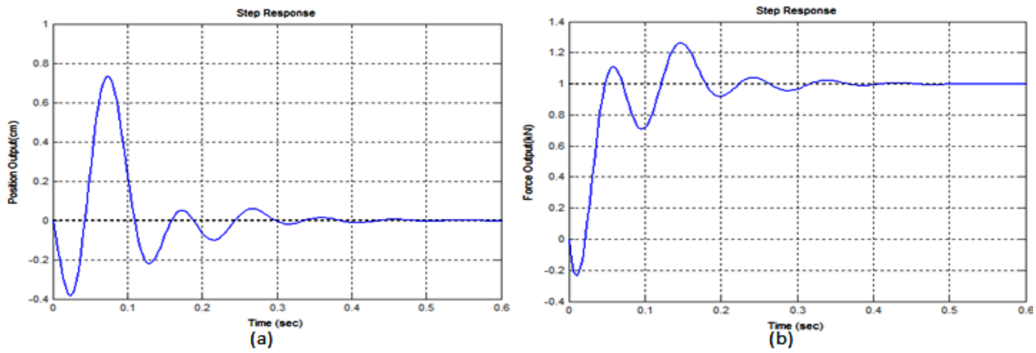

Fig.9. Position and Force of the system with unit step force command using PSO

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Fig.9 shows the response of the plant with the unit step force command using PSO. It can be found that the proposed controller gives quite well performance.
It can also be noted from Figs.8 (b) and 9 (a) that this method also proves to be suitable to reduce the couplings between position control and force control.

It can be seen from Fig. 7 that the bandwidth and performance of plant are significantly improved by the pre- and post-compensator weights. The shaped plant obtained has large value of gains at low frequencies for performance and small value of gains at high frequencies for noise attenuation. Hence, the robust requirement is satisfied with these weighting functions.

VI.CONCLUSION

In this paper, a new technique for designing a fixed structure robust H_∞ loop shaping controller is demonstrated which can be applied to obtain a robust controller for a MIMO electro-hydraulic servo system. The benefit of this proposed technique is that we can select the structure of controller and its order according to our choice and requirement. Stability margin (ε) is used to indicate the robustness and performance of the proposed controller based on the notion of classical H_∞ loop shaping. This stability margin is taken as the objective function for searching the optimal solution for controller parameters by using GA and PSO method. These evolutionary algorithms provide simple and optimal solution to the controller. Comparative performances of GA and PSO for solving such problems has shown that these optimization techniques solve the design problems effectively but the number of iterations for convergence in PSO are much lesser than the iterations required for convergence in GA. Simulation results illustrate that the present design methodology is best suited and also quite helpful in practical applications.

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