International Journal of Computer Information Systems and Industrial Management Applications.
ISSN 2150-7988 Volume 4 (2012) pp. 459-466

Design of Fixed Order Controller by Using Particle Swarm Optimization and System Simulation

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***Abstract*: Design of fixed order controllers is an open problem which takes controller complexity into account. Different solutions exist in literature for the fixed order controller design problem. However, major difficulty in these results is that they are not simple to develop an algorithm that guarantees the decisive solutions coupled with computations. To overcome this difficulty H_∞ loop shaping control under an order specified controller has been proposed. The performance specification is formulated as cost function, which is to be minimized Design. Particle swarm optimization has been adopted for optimization of cost function and parameters of the specified controller. To check the success of proposed techniques, resulting controller parameters are evaluated via system simulations. Simulation results demonstrate the efficiency of proposed technique.**

Keywords: Particle swarm, cost function, velocity, inertia and controller.

I. Introduction

There is close link between the history of the development of control theory and computational methods available at that time [1]. Designing controller for stabilizing complex plant and achieving a specific performance is generally a difficult task. Both computation and implementation of such controllers are serious issues to be dealt with control system design. There are different approaches to simplify the design process; an alternative is to minimize the closed loop performance index by a fixed order controller [2].

The controllers obtained from standard design techniques have generally much higher order than that of the plant. As order of plant may be high, designing full order controller narrows the possibility of use in practical application, that's why there has been increasing and considerable interest in designing low, fixed order controllers but there are basic difficulties inherent to low, fixed order controller design [3].

In the field of control engineering fixed order controller design are gaining increasing interest, one of the reasons is that classical controller design techniques lead to higher order controllers and are complicated to put into operation [4, 5].

Designing controller for stabilizing complex plant and achieving a specific performance is generally a difficult task. There are different approaches to simplify the design process. An alternative is to minimize the closed loop performance index by a fixed order controller [6, 7]. However, there are basic difficulties intrinsic to low; fixed order controller design, such as to find the best possible values of controller gain or optimal performance.

Designing a controller means choosing the suitable gains. The main thing to note is that if the calculated value of gain is too large, the response will vary with high frequency. On the other hand, having too small gains would mean longer settling time. Thus, finding the best possible value for gain is the most important concern in controller design [8]. Generally, the overall design procedure is iterative between controller design and cost function (CF)[1] evaluation [9]. If performance is not satisfactory one has to fine-tune the controller parameters after using Ziegler-Nichols (Z-N)[2] tuning rule, which gives an educated guess for controller parameter values or with adjusting some weighting functions in CF used to synthesis the controller [10].

A population of particles is initialized with random positions and velocities and a function is evaluated, using the particle's positional coordinates as input values. Positions and velocities are adjusted and the function evaluated with the new coordinates at each time step. When a particle discovers a pattern that is better than any it has found previously, it stores the coordinates in a vector. The difference between (the best point found by so far) and the individual's current position is stochastically added to the current velocity, causing the trajectory to oscillate around that point. Further, each particle is defined within the context of a topological neighborhood comprising itself and some other particles in the population.

[1] measure of performance
[2] used to tune the PID controller parameters

The stochastically weighted difference between the neighborhood's best position and the individual's current position is also added to its velocity, adjusting it for the next time step. These adjustments to the particle's movement through the space cause it to search around the two best positions [11, 33].

The variables and are random positive numbers, drawn from a uniform distribution and defined by an upper limit, which is a parameter of the system. In this version, the term variable is limited to the range for reasons that will be explained below. The values of the elements in are determined by comparing the best performances of all the members of 's topological neighborhood, defined by indexes of some other population members and assigning the best performer's index to the variable . Thus, represents the best position found by any member of the neighborhood [12, 29].

The random weighting of the control parameters in the algorithm results in a kind of explosion or a "drunkard's walk" as particles' velocities and positional coordinates careen toward infinity. The explosion has traditionally been contained through implementation of a parameter, which limits step size or velocity. The current paper, however, demonstrates that the implementation of properly defined constriction coefficients can prevent explosion; further, these coefficients can induce particles to converge on local optima [13].

An important source of the swarm's search capability is the interactions among particles as they react to one another's findings. Analysis of inter particle effects is beyond the scope of this paper, which focuses on the trajectories of single particles.

A. Simplification of the System

The analysis by stripping the particle swarm algorithm down to a most simple form; we will add things back in later. The particle swarm formula adjusts the velocity $\vec{v}_i$ by adding two terms to it. The two terms are of the same form, i.e., $\varphi(\vec{p}-\vec{x}_i)$, where $\vec{p}$ is the best position found so far, by the individual particle in the first term, or by any neighbor in the second term. The formula can be shortened by redefining P_{id} as follows:

$$p_{id} \leftarrow \frac{\varphi_1 P_{id} + \varphi_2 P_{gd}}{\varphi_1 + \varphi_2} \tag{1}$$

Accordingly, initial investigation can be simplified by looking at the behavior of a particle whose velocity is adjusted by only one term

$$V_{id}(t+1) = V_{id}(t) + \phi(P_{id} - x_{id}(t)) \tag{2}$$

Where, $\phi = \phi_1 + \phi_2$. This is algebraically identical to the standard two-term form.

When the particle swarm operates on an optimization problem, the value of $\vec{p}$ is constantly updated, as the system evolves toward an optimum. In order to further simplify the system and make it understandable, we set $\vec{p}$ to a constant value in the following analysis. The system will also be more understandable if we make φ a constant as well; where normally it is defined as a random number between zero and a constant upper limit, we will remove the stochastic component initially and reintroduce it in later sections. The effect of φ on the system is very important and much of the present paper is involved in analyzing its effect on the trajectory of a particle. The system can be simplified even further by considering a one-dimensional (1-D) problem space and again further by reducing the population to one particle. Thus, we will begin by looking at a stripped-down particle by itself, e.g., a population of one 1-D deterministic particle, with a constant p . Thus, we begin by considering the reduced system

$$\begin{cases} v(t+1) = v(t) + \phi(p - x(t)) \\ x(t+1) = x(t) + v(t+1) \end{cases} \tag{3}$$

Where p and φ are constants. No vector notation is necessary and there is no randomness [14].

In [14], found that the simplified particle's trajectory is dependent on the value of the control parameter φ and recognized that randomness was responsible for the explosion of the system.

In recent years, particle swarm optimization (PSO) procedure appeared as promising technique for managing the optimization problems. Recently PSO is used to design robust controllers for dynamics of multi-machine system. PSO is population based optimization technique that has many advantages over other classical optimization procedures. The PSO is a general purpose optimizer that solves the wide range of optimization problems, thus the PSO technique can be easily adapted to suit various categories of optimization problem [15, 30].

Most industrial applications use simple controllers such as PI and PID controllers. Other complicated controllers e.g. H∞ etc are hardly used. The goal in this paper is to design a controller with simple structure which has low, fixed order and retains stability. The fixed order H∞ controller design approach is proposed by using PSO along with the concepts developed in [16, 32].

The nominal plant has been shaped by choosing the weighting functions; cost function to be minimized and maximized as the stability margin of the shaped plant. A set of controller parameters p in pre- specified controller K (p) is optimized by using PSO. The designed controller has been implemented in the nominal plant.

B. Statement of the Problem

A linear system with known transfer function given in Eq. (4), it is assumed that plant, described by transfer function under goes certain, unknown numerator denominator perturbation or co-prime factor uncertainties.

$$G(s) = \frac{551 - 13e^{-0.12S}}{(s^2 + 43.26s + 536.9)} \tag{4}$$

A basic feedback SISO system shown in Fig.1, the plant has transfer function *P* and the controller has transfer function *K*. the signal *v* represents a disturbance acting on the system and *z* is control system output.

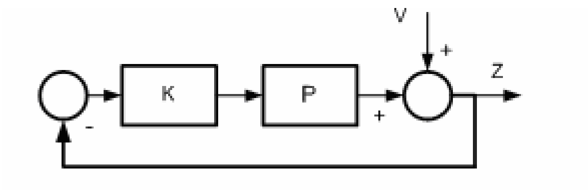

Figure1. SISO feedback loop

The objective of this paper is to design a robust controller, which holds simple structure with lower order that maintains the robustness and meet the performance specifications. Our scope of design is a single output single input (SISO) plant, but it can be extended to a multi input multi output (MIMO) plant.

The problem is formulated as the minimization of performance index subject to H_∞ robust stability constraints. Hence the problem of the synthesis of controller is one how to solve above minimization problem. In this paper evolutionary techniques are used because these techniques are robust and likely to converge at global optimum Particle Swarm Optimization based controllers, thereby providing improved performance with respect to overshoot, settling time and oscillations.

The paper is arranged as follows: following the introduction about background literature and problem statement is presented in last paragraph. Section II describes H_∞ robust control problem, the conventional H_∞ loop shaping design procedure is presented in section III, section VI discusses the detailed procedure of proposed schemes to design of low, fixed order controller using Particle swarm optimization, section V presents discussion on simulation results, finally conclusion is summarized in section VI.

II. Standard H∞ robust control problem

Considering a generalized plant *P(s)* in the general H_∞ configuration as shown in Fig. 2, it will include plant model and disturbance model and the interconnection structure between the plant and the controller. Moreover, if *P*(s) is being used to formulate a design problem, then it will also include weighting functions. *w* denotes exogenous inputs; commands, disturbances and noise, and z denotes exogenous outputs error signals to be minimized and *y* is controller inputs for the general configuration, for example commands, measured plant outputs, measured disturbances etc.[17] . The objective is to find the stabilizing controller to minimize the output *z*; it is equivalent to minimizing the H_∞ norm of the transfer function from *w* to *z* [18].

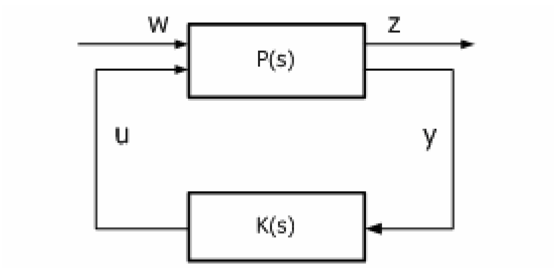

Figure 2. General H_∞ Configuration

The closed loop transfer function from *w* to *z* can be obtained directly as:

$$Z = F_l(P,K)w \tag{5}$$

Where $F_l(P,K) = P_{11} + P_{12}K(I - P_{22}K)^{-1}P_{21}$ is called the lower fractional transformation of P and K. Therefore, the optimal H_∞ control problem is to minimize the H_∞ norm of $F_l(P,K)$, i.e., $\|F_l(P,K)\|_\infty$

A. *H∞ Robust Stabilization*

In this approach the shaped plant is formulated as a normalized co -prime factor which separates the plant G_s into normalized factors nominator N and denominator M. One of the important uncertainties is co-prime factor uncertainty or numerator denominator perturbations [19, 31]; this uncertainty is repeatedly used in controller design procedure, where the objective is to maximize the magnitude of uncertainty such that robust stability is maintained [20].

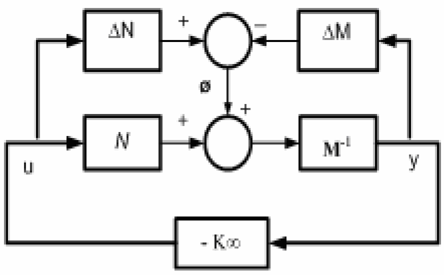

Figure 3. Co-prime factor robust stabilization problem

The normalized co-prime factorization of the shaped plant is $G_s = W_1 G_0 W_2$, then a perturbed plant G_Δ is then can be written as:

$$G_\Delta = (N + \Delta N)(M - \Delta M)^{-1} \tag{6}$$

Where, ΔM and ΔN are stable unknown transfer functions representing the uncertainty in the nominal plant model G_0. satisfying $\|\Delta N \quad \Delta M\|_\infty \leq \varepsilon$, where ε is uncertainty boundary called stability margin. To maximize this class of perturbed model such that the configuration shown in Fig. 3 is stable, a controller K_∞ that stabilize the nominal closed loop system and minimizes gamma must be found by Eq. (7),

$$\gamma = \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_s K_\infty)^{-1} M^{-1} \right\|_\infty \tag{7}$$

Where γ is the H_∞ norm from $\emptyset$ to $\begin{pmatrix} u \\ y \end{pmatrix}$ and $(I + G_s K_\infty)^{-1}$ is the sensitivity function, the lowest achievable value of gamma and corresponding maximum stability margin epsilon are calculated by Eq. (8)

$$\gamma = \varepsilon_{\max}^{-1} = \sqrt{I + \rho(XZ)} \tag{8}$$

Where ρ represent maximum Eigen value and for minimal state space realization (A, B, C, D) of G(s),

$$G(s) = D + C(SI - A)^{-1}B \tag{9}$$

Z is the unique positive definite solution to the following algebraic Riccati equation [21]

$$(A - BS^{-1}D^{T}C)Z + Z(A - BS^{-1}D^{T}C)^{T} - ZC^{T}R^{-1}CZ + BS^{-1}B^{T} = 0 \tag{10}$$

X is the unique solution of the following algebraic Riccati equation

$$(A - BS^{-1}D^{T}C)^{T}X + X(ABS^{-1}D^{T}C) - XBS^{-1}B^{T}X + C^{T}R^{-1}C = 0 \tag{11}$$

Where, A, B, C, and D are state space matrices of G, $S = I + D^{T}D$ $R = I + DD^{T}$ Notice that formulae simplify considerable for a strictly proper plant i.e. when D=0.

Then, a minimal state space realization of the normalized left co-prime factorization is given by [22]

$$\begin{bmatrix} N & M \end{bmatrix} = \begin{bmatrix} A + HC & B + HD & H \\ R^{-1/2}C & R^{-1/2}D & R^{-1/2} \end{bmatrix} \tag{12}$$

Where $H = -(BD^{T})R^{-1}$

B. *Controller Structure Selection*

Assume that $K(p)$ is structure specified controller. The structure of controller is specified before starting the optimization process. A set of controller parameters p is evaluated to maximize/minimize objective function. The controller structure is taken as vector p of the controller parameters is given by $p = [K_p, K_i]$. The Controller $K(p)$ can be written as:

$$K(p) = W_1 K_\infty W_2 \tag{13}$$

Assume that W_1 and W_2 are invertible, then

$$K_\infty = W_1^{-1}K(p)W_2^{-1} \tag{14}$$

W_2 is chosen as identity which employees that sensor noise is negligible, then

$$K_\infty = W_1^{-1}K(p) \tag{15}$$

The infinity norm of transfer function T_{wz} can be written as

$$\gamma = \|T_{wz}\|_\infty = \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_s K_\infty)^{-1} M^{-1} \right\|_\infty \tag{16}$$

In this paper evolutionary techniques particle swarm has been adopted to find the optimal values of controller parameters p^* in stabilizing controller $K(p)$ such that the $\|T_{wz}\|_\infty$ is minimized.

III. CONVENTIONAL LOOP SHAPING DESIGN

According to conventional H_∞ loop shaping design procedure, following steps can be applied:

1) Shape singular values of the nominal plant G_0 with frequency dependent pre- and post-compensators W_1 and W_2 such that the achieved loop-shape i.e. the singular values of the shaped plant $G_s = W_1 G_0 W_2$ satisfies the closed-loop performance requirements. For selecting the weights some guide lines available in [23]. Typically weights are selected such that the open loop plant has the following properties:

- for achieving good performance tracking, good disturbance rejection require , large open loop gain as a rule at low frequency range is necessary
- to achieve good robust stability and sensor nose rejection require a small open loop gain as a rule at high frequency range is necessary
- to achieve the desired bandwidth of controller, selection of crossover frequency (a frequency at which the open loop of the shaped plant intersect with the 0dB line) is important. We select crossover frequency to achieve the desired bandwidth of our controller.

The weighting functions are chosen as:

$$W_1 = K\frac{s + \alpha}{s + \beta} \tag{17}$$

Where K, α, β are positive numbers, β is selected as small number ($\ll 1$) for integral action.
The shaped plant is shown in Fig.4

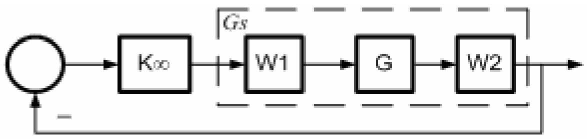

Figure 4. Shaped Plant

2) Minimize the H_∞ -norm of transfer function matrix, T_{wz} o to find the overall stabilizing controller *K*.

$$\gamma = \inf_{stabK} \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_s K_\infty)^{-1} M^{-1} \right\|_\infty \tag{18}$$

As the resulting optimal gamma is the measure of robustness of desired loop shape, if optimal gamma is less than 4, it means that the designed loop shape is incompatible with robust stability and hence designer should go back to step 1 to design better loop shape (readjust weights).

The gamma optimal can be determined by procedure explained in [24].

$$\gamma = \varepsilon_{\max}^{-1} = \sqrt{I + \rho(XZ)} \tag{19}$$

Where X and Z are solution of two algebraic Riccati equations and ρ represent maximum Eigen value

3) Synthesize a controller K_∞ that satisfies negative feedback, achieves a robust stability margin that is slightly less than the computed. The reason for this is that optimal controllers cannot be written in observer form, which is often desirable, and do not roll-off at high frequency (select ε less than ε optimal).

$$\|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_s K_\infty)^{-1} M^{-1} \right\|_\infty \tag{20}$$

Controller K_∞ is obtained by solving the control problem in Eq. (21)

$$\|T_{zw}\|_\infty = \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_s K_\infty)^{-1} \begin{bmatrix} I & G_s \end{bmatrix} \right\|_\infty \le \varepsilon^{-1} \tag{21}$$

4) The final controller K_{final} is constructed by multiplying the K_∞, with weighting functions W_2 and W_2 as depicted in Fig.5.

$$K(s)_{final} = W_1 K_\infty W_2 \tag{22}$$

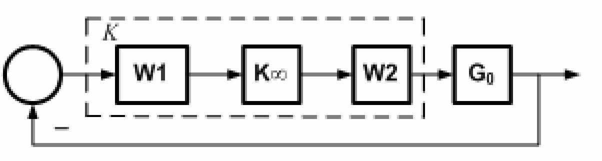

Figure 5. Final Controller

A controller K_∞ stabilizes the original closed loop system and minimizes gamma [20].

$$\gamma = \underset{k}{\overset{\inf}{stab}} \left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_s K_\infty)^{-1} M^{-1} \right\|_\infty \tag{23}$$

A. *Weight Selection*

For selecting the weights, some guide lines are available in [17]. The weighting functions are chosen as:

$$W_1 = K \frac{s+\alpha}{s+\beta} \tag{24}$$

Where $K, \alpha, and\, \beta$ are positive numbers, β is selected as small number (<< 1) for integral action.

IV. Design of Fixed Order Controller using Particle Swarm Optimization

In PSO, the potential solution called particles fly through the problem space by following the current optimum particles with an adoptable velocity that is dynamically modified according to its own flying experience and also the flying experience of other particles .Further each particle has a memory and has capable of remembering the best position in the search space ever visited by it [9].

The position corresponding to the best fitness is known as P_{best} and the overall best out of all particles in the population called *gbest.*

$$V_{id} = w \times V_{id} + c_1 \times Rand() \times (P_{id} - x_{id}) \\ + c_2 \times Rand() \times (g_d - x_{id}) \tag{25}$$

$$x_{id} = x_{id} + V_{id} \tag{26}$$

V_{id}: Velocity of each particle in each dimension
i: Particle
D: Dimension W: Inertia Weight
$C\ c_2$: Constants *Rand()* : Random
P_{id} : Best position of each particle
g_d : Best position of swarm
x_{id} : Current position of each particle in each dimension

Particle swarm optimization has many advantages over other conventional optimization techniques:

- PSO is almost derivative free.
- PSO has flexibility to be incorporated with other optimization techniques.
- PSO has fewer parameters to adjust.
- PSO is comparatively easy to put into operations, such as logical operations
- PSO has ability to escape local mini-ma
- PSO does not need an initial solution to begin its process of iterations.

The model of the plant is given in Eq. (28):

$$G(s) = \frac{551.3e^{(-0.12s)}}{(s^2 + 43.26s + 536.9)} \tag{28}$$

The p controller structure is taken as vector p of the controller parameters is given by the $p = \lfloor k_p \quad k_i \rfloor$. From Eq.(14) Controller $K(p)$ can be written as:

$$K(p) = W_1 K_\infty W_2 \tag{29}$$

It is assumed that W_1 is invertible and W_2 =1

$$K_\infty = W_1^{-1} K(p) \tag{30}$$

By substituting Eq. (30) into Eq. (21), we have

$$J_{cost} = \left\| \begin{bmatrix} I \\ W^{-1}K(p) \end{bmatrix} (I + G_s W^{-1} K(p)^{-1} (I \quad G_s) \right\|_\infty \tag{31}$$

A. Sequential scheme for proposed approach

The steps for the sequential scheme for proposed approach can be described as follows:

Step1. Shape the singular values of the nominal plant by selecting W_1 and W_2 then calculate the gamma using Eq. (19). If gamma is greater than 4, it shows that weighting functions are incompatible; the weight W_1 will be adjusted.
Step2. Initializes several sets of population parameters *p a*s population of particles, where *p* is considered as a vector of controller parameters.
Step3. Specify the controller structure; evaluate the cost function of each particle by using Eq. (31) according to cost function.
Step4. At each generation the velocity of each particle is calculated by using Eq. (25) and positions of next is according to Eq. (26).
Step5. If current iteration is less than maximum iterations then stop, go to step 3
Finally, checks the performance in both frequency and time domain. The flow chart of the proposed scheme as shown in Fig.5:

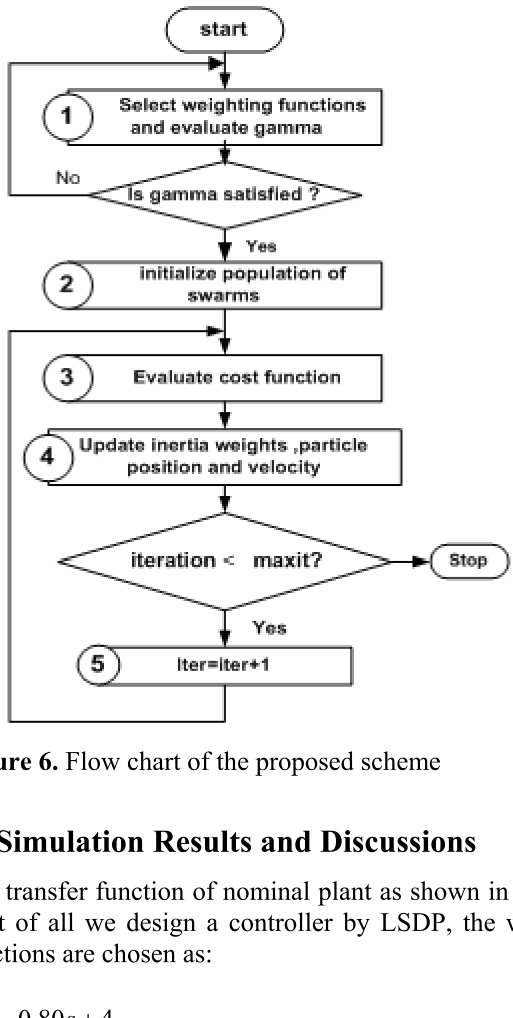

Figure 6. Flow chart of the proposed scheme

V. Simulation Results and Discussions

The transfer function of nominal plant as shown in Eq. (28). First of all we design a controller by LSDP, the weighting functions are chosen as:

$$W_1 = \frac{0.80s+4}{s+0.001}, \qquad W_2 = I \tag{32}$$

Where I is the identity matrix, with these weighting functions the shaped plant is computed as:

$$G_s(s) = \frac{413.5s + 2205e^{-0.12S}}{s^3 + 43.26s^2 + 536.9s + 0.5369} \tag{33}$$

The stabilizing controller K_∞ can be obtained by Matlab Code,

$$K_\infty(s) = \frac{413.5s + 2205}{s^3 + 43.36s^2 + 5369s + 0.5369} \tag{34}$$

By putting Eq. (34) and Eq. (32) in Eq. (22), then $K(s)_{final}$ can be obtained as:

$$K(s)_{final} = \frac{310.1s^2 + 3308s + 8221}{s^4 + 43.26s^3 + 537s^2 + 1.074s + 0.05369} \tag{35}$$

The controller obtained by conventional techniques Eq. (35) is of 4^{th} order and its structure is complex as well, obviously it is difficult to implement practically for industrial application. Hence the advantage of fixed order can be obtained from proposed approach. A PI controller is investigated as a fixed order controller, K_p and K_i are the controller parameters that would be evaluated by using PSO. The controller structure is expressed in Eq. (36)

$$K(p) = K_p + \frac{K_i}{s} \tag{36}$$

The simulation was carried out using representation of particles. The size of initial population is 10 particles. Algorithm converged in second iterations, and gave optimal cost function of 1.395. Fig.7 shows the plot of convergence of cost function versus iterations of PSO.

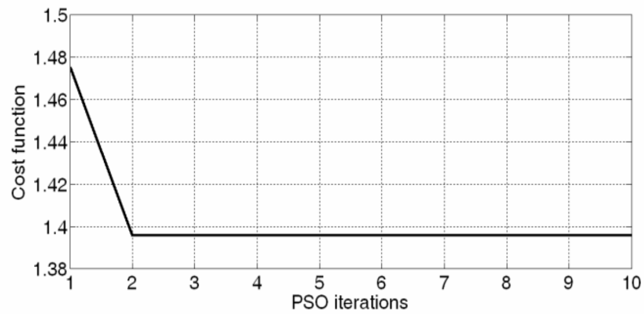

Figure 7. Convergence of cost function vs. iteration of PSO

The optimal solution of controller parameters was obtained which has satisfied stability margin of 0.716, it shows that PSO can find optimal solution. The computed optimal values of controller parameters are shown in Eq. (37)

$$K(p)^* = 0.400 + \frac{1.00}{s} \tag{37}$$

Evidently, the controller obtained by conventional techniques is of high order and its structure is very complex, obviously difficult to implement practically. Thus the controller is Eq. (35) is 4^{th} order controller and has complex structure. Hence the advantage of fixed structure can be obtained from the proposed techniques.

The step response of the control system with optimized controller parameters by using PSO is shown in Fig.8 the step response presents rise time 1.25 sec., about 2% overshoot and the settling time is about 1.23 sec. the results obtained clearly shows the effectiveness of proposed scheme.

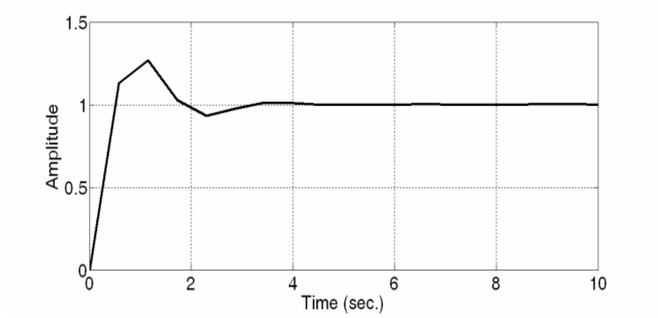

Figure 8. Step response obtained by PSO

VI. Conclusion

In this paper, a new approach for designing a fixed order robust controller is proposed. In the proposed design approach controller parameter optimization and minimizing the cost function is based on PSO. The performance of control system using controller designed by using the proposed approach was tested for closed loop step response. The simulation results show that the algorithm converges and system has satisfactory step response.

Moreover, in cases where complex mathematical calculations, algebraic optimization and fraction of polynomial matrices are involved, PSO is a better alternative to solve an optimization problem. The proposed approach will enable the practicing engineers to employ the approach for designing of controller with low, fixed order, like PID controllers, which have high acceptances in industrial applications.

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