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Design and Implementation of Optimized Controller Tuning of a Real Time Coupled Spherical Tank Process used in Process Industries

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Abstract

This paper proposes the optimized controller tuning for a real time coupled spherical tank process used in various process industries like chemical industries, waste water treatment plant, petrochemical industries, etc. In all process industries spherical tank process plays a vital role in each stages of the process. Spherical Tank has a uniformly stressed strong and complex structure used in various process industries. The varying diameter of Spherical Tank makes the process complicated and becomes a nonlinear system; this nonlinearity can be overcome by including the optimized tuning of a PID controller. The Particle Swarm Optimization (PSO) provides better results for process industries in-terms of easy storage, complete maintenance free operation, effective cleaning, and high stability output. The effectiveness of the Spherical Tank Process used in process industries is analysed based on optimized controller tuning and the performance is verified using the error criteria and by the time domain analysis. The optimized PSO tuning method provides enhanced time domain specifications, smooth response curve and minimized error compared to other controller tuning methods. The results are analysed using Matlab software.

Keywords: PID Controller, PSO, Nonlinear Process, Spherical tank process, Matlab.

1. Introduction

The Proportional Integral Derivative (PID) controller is a standard control algorithm used to tune the linear process in a classical way. Now a day the researchers are mainly concentrating on the adaptive and optimized controller which deals with more complicated process. Many researchers develop various evolutionary algorithms for the tuning of PID controller even though Zeigler Nichols PID tuning is the base for all tuning methods. To increase the efficiency and stability of the Spherical Tank Process optimized PID tuning method is widely used. Comparing with conventional PID tuning methods optimized PID tuning provides better applications in the liquid storage process. Optimized PID control algorithm used to identify the specific control law for the proposed system and to achieve the optimality criterion of the particular system. The control law consists of a cost function which includes state variables and control variables. An optimized control algorithm is described by the set of differential equations in which the control variables minimizes the cost function of the system. Tuning of PID controller in a Spherical Tank Process is an important criterion because of the transform in nature shape gives increase to the nonlinearity.

The PID controller was proposed by Norm Minorsky in 1922. Now days the researchers are mainly concentrating on the adaptive and optimized controller which deals with more complicated process. Suji Prasad et al proposed the particle swarm optimization based PID controller tuning used for the performance analysis [1]. S.Nithya et al proposed the model based tuning methods of PID controller for a real time systems [22]. Based on the literature review, the proposed system includes classical PID tuning and improved optimized PID tuning for a coupled spherical tank process. Classical PID tuning method is applicable for the linear process and for a nonlinear process improved optimized PID tuning is proposed. Spherical tank system is a difficult and important criterion due to its nature of the shape which can increases the nonlinearity of the process. To overcome the nonlinearity of the spherical tank process improved optimized control techniques are widely used.

2. Mathematical modeling of a conical tank system

In the proposed system mathematical modeling of a spherical tank system is derived and the final transfer function is obtained. The obtained transfer function is used to get the simulation and the real time response for various tuning methods. The response curves are plotted for each tuning values. Mathematical modeling of spherical tank system is derived based on the structure and the output transfer function is obtained. The output equations are well formulated and assumed as a process model structure with optimization. Optimized PID tuning is an effective tool for tuning of a controller. To derive the mathematical modeling of a spherical tank, the input of the process should be initialized and the input and output relations should be known and should be properly defined. The primary task is to understand the system and the system need to be investigated to realize the incident of nonlinearity present in the system dynamics. Now days, the utility of Improved Particle Swarm Optimization Algorithm is extensively increasing because of its high accurate, fast and optimal responses compared with conventional techniques [17]. The proposed spherical tank system, identified as a nonlinear complex structure is shown in Fig. 1.

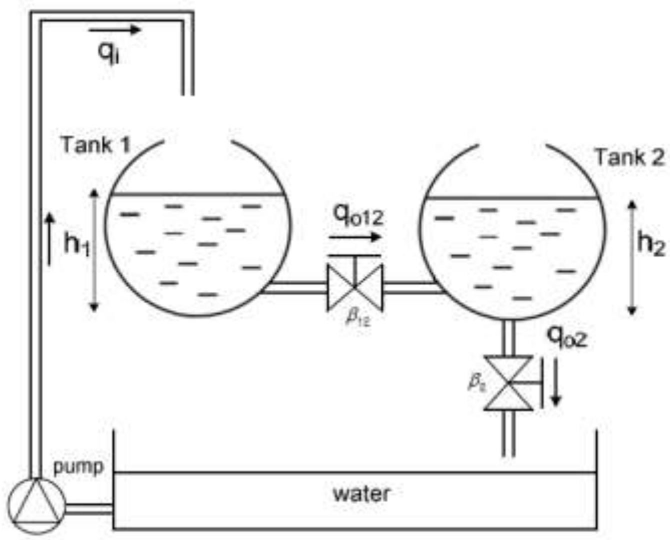

Fig:1 Structure of coupled spherical tank system

The nonlinear equations are as follows,

$$\frac{dh_1(t)}{dt} = -\frac{\beta_{12} a_{12}}{A_1}\sqrt{2g\left(h_1(t)-h_2(t)\right)} + \frac{k}{A_1}u(t) \quad \text{—(1)}$$

$$\frac{dh_2(t)}{dt} = -\frac{\beta_2 a_2}{A_2}\sqrt{2gh_2(t)} + \frac{\beta_{12} a_{12}}{A_2}\sqrt{2g(h_1(t)-h_2(t))} \quad \text{—(2)}$$

Where,

A1 & A2 => Cross section area of tank 1 &2

a2 => Cross section area of outlet of tank 2

a12 => Cross section area of jointed pipe

β2 => Value ratio at the outlet of tank 2

β12 => Value ratio between tank 1 and tank 2

g => Gravity

k => Gain of pump

$$G(s) = \frac{H_2(s)}{U(s)} = \frac{K}{T_{12}T_2 s^2 + (T_{12}+2T_2)s + 1} \quad \text{—(3)}$$

$$T_{12} = \frac{A_1}{\beta_{12}a_{12}}\sqrt{\frac{2(\overline{h_1}-\overline{h_2})}{g}},\ T_2 = \frac{A_2}{\beta_2 a_2}\sqrt{\frac{2\overline{h_2}}{g}},\ \mathrm{K} = \frac{kT_2}{A_2}$$

Equation (3) is the linearized form of equation (1) & equation (2) describes about the transfer function of a real time spherical tank process used in process industries. The obtained transfer function is tuned with different tuning methods and the response curve is plotted. The plotted results are compared based on the time domain specifications and error values. The best tuning method is concluded based on the plotted results.

3. Classical PID tuning methods

"PID" stands for proportional, integral, and derivative controller. A proportional integral derivative controller consist of the elements with the three functions. The conventional linear PID controller is combined by the following three terms linearly, the control error, the integral of the error, and the derivative of the error. Many researches and practices show that it is helpful to the control results when the three terms are constructed in some kind of nonlinear function forms. There are considerable papers present different ways to design nonlinear PID controller. Advanced PID controllers are the modification of linear PID controllers by using several special functions to create more attractive engineering applications.

A. Astrom and Hagglund Tuning Method

In 1984, Karl Astrom and Tore Hagglund of the Lund (Sweden) Institute of Technology proposed a less risky alternative to the Ziegler-Nichols open-loop test. This method produces a continuous swinging of the process variable but with the amplitude of those swinging is limited to a safe range. The Astrom-Hagglund method works by forcing the process variable into a limit cycle as shown in the "relay test" graphic. Initially all the three PID terms will be disabled for the time being and the controller uses an on/off relay to apply a step input to the process. It then holds the control effort constant and waits for the process variable to exceed the set point. At that point, it applies a negative step and waits for the process variable to drop back below the set point. Repeating this procedure each time the process variable passes the set point in either direction forces the process variable to oscillate out of synchronization with the control effort but at the same frequency [25].

PID Parameters:

Proportional constant: $Kc = 5Tm/6(Km\ \tau_{m)} = 1.62$

Integral constant: $Ti = 1.45\ \tau_m = 0.02$

Derivative constant: $Td = 0.28\ \tau_m = 1.31$

B. Internal model control

Internal model control is model based controller structure that provides a suitable framework for satisfying our objectives. The IMC structure makes use of a process model to infer the effect of immeasurable disturbance on the process output and then counteracts that effect. The controller consists of an inverse of the process mode. IMC design procedure depends exclusively on two factors: the complexity of the model and the performance requirements. The IMC based PID controller algorithm is robust and simple to handle the uncertainty in model. This method seems to be a useful trade-off for the performance of the closed loop system. It achieves robustness to model inaccuracies with a single tuning parameter. The IMC design procedure can be used to solve quite a few critical problems especially at the industrial level (using the concept of designing a model of the actual plant process). It also gives good solutions to processes having a significant time delay which actually happens when working in a real time environment. While tuning the controllers the tuning parameter λ is varied from minimum value. According to that various effects of discrepancies enter in the system thus, best performance is achieved. Hence, a good filter structure is one for which the optimum λ value gives the best PID performance.

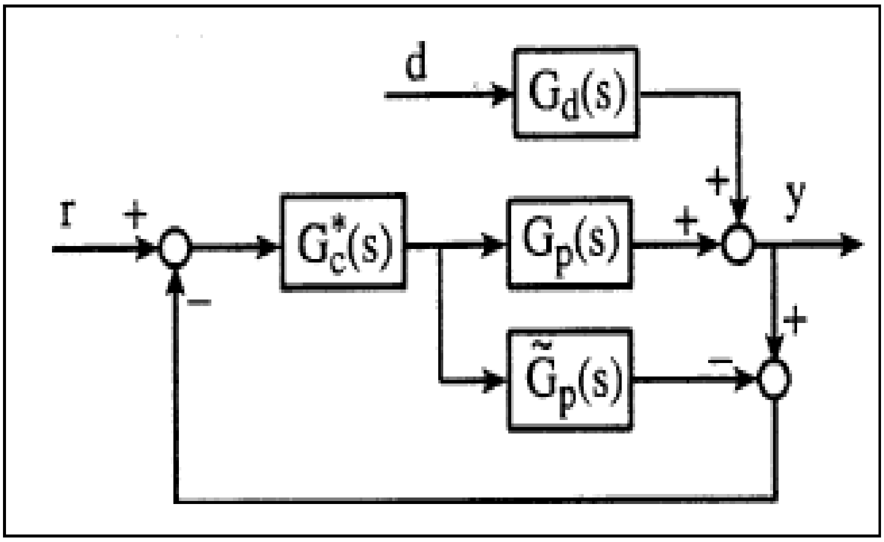

Figure.2. Block Diagram of Internal Model Controller

PID Parameters:

Proportional constant:

Kc= 0.89

Integral constant:

Ti= 0.019

Derivative constant*:*

Td=1.11

4. PSO tuning for a spherical tank system

Particle Swarm Optimization is a strong random functional technique is initiated by the scattering of particles in the search space and swarm intelligence. PSO is a concept related to the problem solving based on public interaction. Particle Swarm Optimization method was invented by James Kennedy and Russell Eberhart. This method exploits a numerous representatives that compose a flock scattering around in the search space and come across for the high quality solution. Each particle in the search space is treated as a point which fine-tunes its airborne terminology according to its personal practice and the airborne information of the additional particles present in the system.

The PSO algorithm has to follow three steps and it has to repeat the steps still reaching the stopping condition.

- Calculate the fitness of each particle.
- Revise individual and global best fitness and positions.
- Revise the velocity and location of each particle.

In the proposed system optimized tuning values are identified based on iteration values. From the classical PID tuning methods best Kp, Ki, Kd values are obtained. The obtained values are used to initialize the PSO tuning method and initialization of PSO tuning includes the parameter initialization process. To introduce PSO, numerous parameters want to be described. Parameter initialization is a process of initiating the dimension of the search space, number of iterations and velocity constants. The dimension of the flock satisfies the necessity of global optimization and working out cost. Initial inputting of the parameters are as per the table. After the completion of the iteration global best and local best values are obtained.

Table.1. Parameter Initialization

Population Dimension	50
Iteration Count	100
Constant Velocity ,c1	2
Constant Velocity ,c2	2

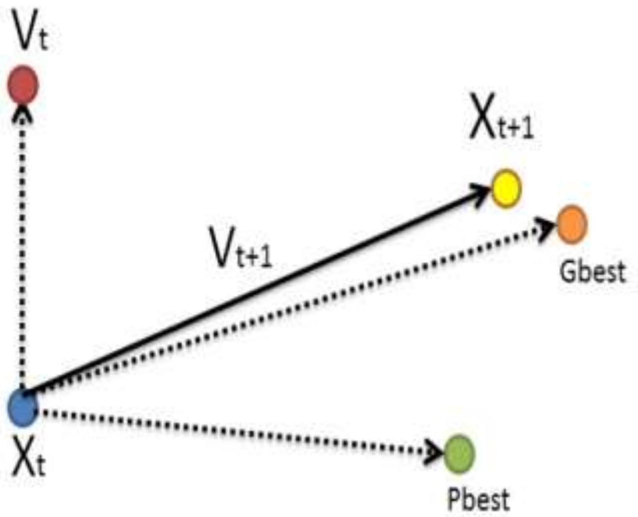

Figure. 3. Vector diagram of PSO

The most significant method of applying the PSO algorithm is to choose the objective function which is used to estimate the fitness of each Particle. Most of the process uses performance indices as an objective function. The objective functions are Mean of the Squared Error, Integral of Time Absolute Error, Integral of Absolute Error, and Integral of the Squared Error. Based on the above objective function various error criteria were calculated for each tuning methods and the error values are compared. The PID controller is employed to reduce the error value and it will be defined more thoroughly based on the error criterion. If the performance indices values are smaller it gives the best results and for higher values it will not provide good results [6].

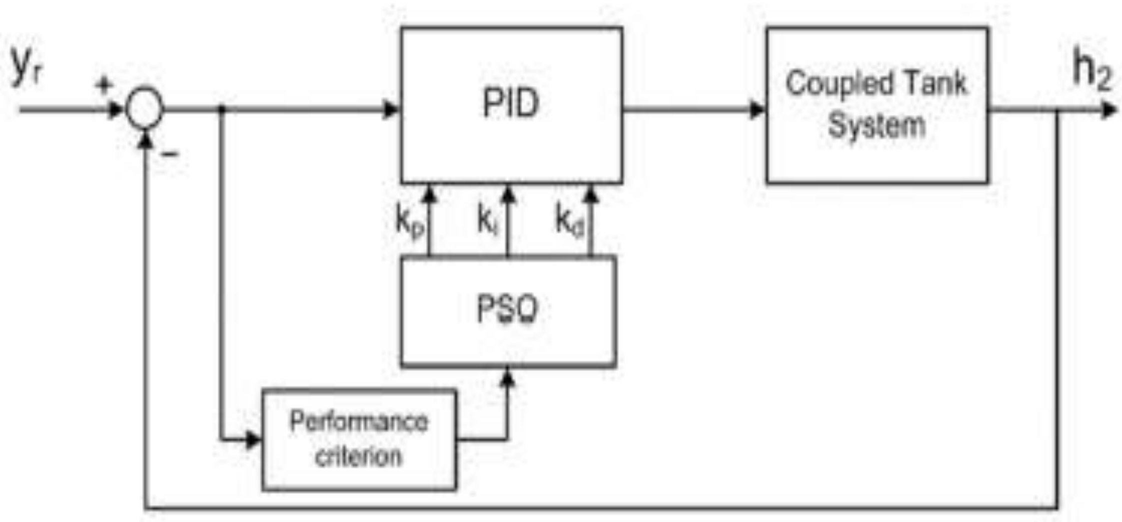

Figure. 4. Block diagram of PSO-PID coupled tank system

Table.2 PID VALUES

Tuning Methods	**Kp**	**Ki**	**Kd**
Astrom & Hagglund	1.62	0.02	1.31
IMC	0.89	0.019	1.11
PSO	0.56	0.009	1.03

The block diagram of PSO-PID based coupled tank system is shown in figure.4. Based on the block diagram by using the improved particle swam optimization method the PID controller is tuned using various tuning methods.PID parameters are calculated using various tuning methods and the Kp, Ki, Kd values are tabulated and best tuning values are analysed.

Performance Index for the PSO Algorithm:

The most critical step in applying PSO is to choose the objective functions that are used to evaluate fitness of each Particle. Some works use performance indices as the objective functions.

1) Integral of the absolute value of the error (IAE)

$$IAE = \int_0^t e(t)^2 \, dt$$

2) Integral of the square value of the error (ISE)

$$ISE = \int_0^t |e(t)| \, dt$$

3) Integral of the time weighted absolute value of the error (ITAE)

$$ITAE = \int_0^t t|e(t)| \, dt$$

4) Mean square error (MSE)

$$MSE = \frac{1}{n^n} \sum_{n=1}^{i} (e(t)^2)$$

The PID controller is used to minimize the error signals, we can define more rigorously, in the term of error criteria: to minimize the value of performance indices mentioned above.

5. Real Time Experimental Setup

The non-linear behavior of the conical tank system is identified by constant input flow rate. The maximum height of the tank is 150 cm. Input to the tank is incremented stepwise, the current to the system is maintained at 4-20 mA and passes all the way through the serial port RS - 232 along ADAM interface unit. Through manual control method, specified transform at input value the output response of the process is documented. Using controller tuning methods the time constant and delay time of a FOPTD process is constructed using tangent method based on its point of inflection. The real time setup of the proposed system consists of two spherical tank process, water reservoir, centrifugal pump, rotameter, electro pneumatic converter and pneumatic control valve. The output signal from the process is interfaced with a computer using ADAM card through RS-232 serial port. Thus the coding were developed using Matlab software and interfaced using ADAM card. The Fig.5 above shows the experimental setup of the automated process.

Figure. 5: Real time setup of coupled Spherical tank system

In Fig. 5 water reservoir is used as a storage tank. Centrifugal pump is used to pump the water from the reservoir and circulates the water throughout the plant. The rotameter is a type of flow meter used to compute the flow rate of liquids and gases in industries. Pneumatic converter converts a 4 to 20 mA input signal to a 3 to 15 psi output signal. The flow rate is controlled by the pneumatic control valve. The pneumatic valve used here is “air to close valve” which is used to adjust the water flow in the conical tank system. The height of the conical tank process is obtained through computational method and broadcasted in the form of current range between (4–20) mA. Hardware and software of the system are interfaced by means of ADAM card. The input to the system is regulated and tuned using optimal tuning method. The control action is performed by executing Matlab coding, based on the hardware interface. The control signal controls the valve position thus controls the level of the coupled spherical tank.

6. Results and Discussion

The response of the coupled spherical tank system using PSO-PID controller is analyzed and the outputs are not. The response of the controllers are estimated and evaluated in the form of rise time, overshoot and settling time with existence of measurement noise. The controller output is evaluated based on the performance index, if the error values are lesser than the controller is considered as a best controller. PSO tuning terminology provides an iteration based analysis were we can get the optimized local best and global best values. This value can be used to get quick steady state response. The Matlab software is used to analyze the results based on controller tuning method and controls the actions automatically. The various PID tuning methods like Astrom and Huggland, IMC method, PSO, methods are compared using the Matlab software.

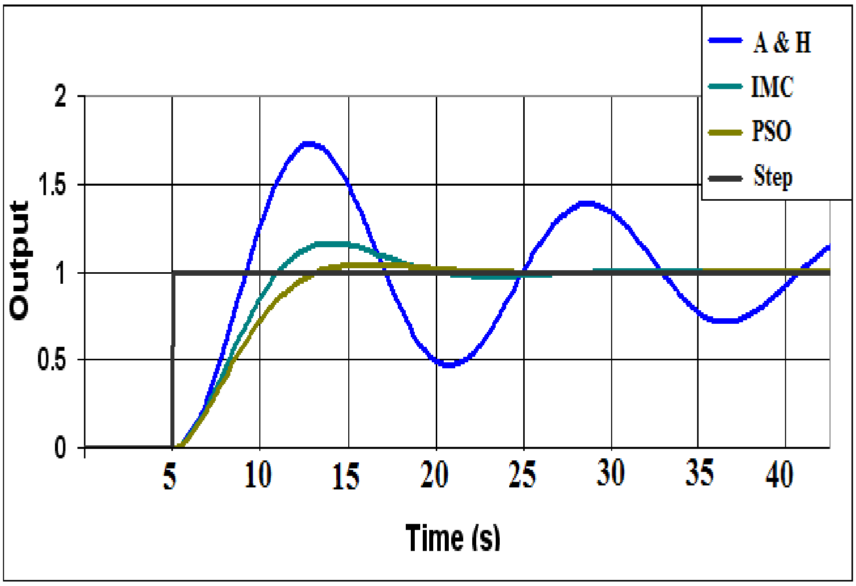

Figure. 6. Matlab Response

Table:3 describes the different types of error values for various tuning methods. This error analysis can be done for the identification of best tuning method. From the above table the error values of PSO tuning method is very much reduced. This shows that PSO tuning is the best tuning method.

Table.3. Error Values

Methods	IAE	ITAE	MSE	ISE
Astrom & Hagglund	67.5	167.8	78.6	145.6
IMC	54.3	146.8	64.3	123.5
PSO	34.5	86.2	23.4	56.7

Table:4 includes the time domain specifications of the various tuning method. Based on the results PSO tuning method offer better output based on improved transient characteristics.

Table.4. Time Domain Specifications

Methods	Rise Time (Sec)	Overshoot (%)	Settling Time (Sec)
Astrom & Hagglund	16	88	87
IMC	10	17	23
PSO	08	12	20

7. Conclusion

PSO based optimized PID controller is capable of providing an enhanced output performance over the traditionally tuned PID controller parameters. Comparing with the classical PID tuning method, the proposed method was more well-organized in improving the step response characteristics such as reducing the steady state error, rise time and settling time in level control of spherical tank employed in the process industries. Comparison graph for the output with time is shown in Fig.6. The entire concept has been configured to implement in the process industries, where, the spherical tank plays a major role. Concluding that the PSO tuning is chosen as the best tuning technique that can be proposed for coupled spherical tank process used in process industries.

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