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Tunning of PID Controller for Paper Machine Headbox using Hybrid PSOABC Algorithm

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Abstract
In paper machine, critical sub-process is Headbox. There are two input and output process in headbox and there will be a noticeable amount of loop interaction. Based on its operation, paper quality is defined. In order to produce paper with good quality, precise control is needed. In this research, Artificial Bee Colony algorithm technique and particle swarm optimization (PSO) are combined to form a hybrid H-PSOABC method to design a head box's proportional integral derivative (PID) controller. Conventional PID controllers are used to make a comparison of robustness and performance of H-PSOABC-PID controller. The comparison is made with respect to ITAE, ITSE, IAE, ISE, time and frequency response.

Keywords: *PID Controller, Headbox, ABC, Zeigler-Nichols (ZN), PSO, Tyreus-Luyben (TL), Paper Machine.*

1. Introduction

In china, around 2000 years ago this paper was developed [1]. Billion dollar of economy is added by making paper [2]. Paper machine is a vital subsystem in the process of paper making [3]. In an efficient way, slurry of water and cellulose are converted by a paper machine [2].

Fourdrinier Machine principles are used in modern paper machines. Reel, calendar, Dryers, Presses, Fourdrinier Table, Head box, Flow spreader are important components of Fourdrinier paper machine. Paper making process is complex process like mass and heat transfer. It is a process of nonlinear and there are parameters that are distributed [3]. High speed machine with better efficiency is needed to make a paper with high quality [4].

Control and modelling process defines the operation of paper machine. It is highly a complex process and it requires various advanced control for the operation of overall process. Various hub processes are included in process of paper and it is a multiple variable process. Between sub-processes, better co-operation is needed to make an efficient control of it [4].

In the process of paper making, "Headbox" is an important sub-system. Steady state movement to wire from pulp is caused by this headbox of paper machine. Stock material is an important process of paper making. On the wire, stock material is distributed uniformly by headbox [5]. There are two types of headbox namely, open type and pressurized. Hydraulic and air cushion are the types of pressurized headbox. Operation of this headbox defines paper's final quality. So it requires a high control as well as monitoring.

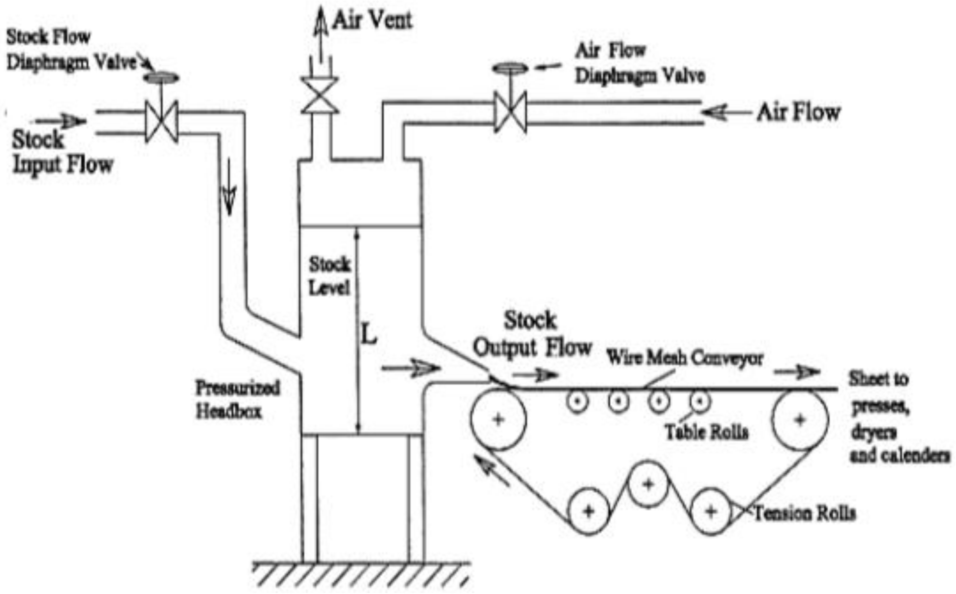

Figure 1: Head box Arrangement [16].

Headbox is a type of multivariable system. It is a nonlinear one. Desired operation of headbox is ensured by a control method. Control method is required due to its complexity and interaction between loops. In this section, a brief survey about headbox design is presented.

Kothari in [6]discussed about various parameters that effects the head box's paper formulation process. Adaptive control technique for paper is proposed by TorstenCegrellet. al.[7]. Sinha and Rutherford presented a in deterministic state variable model and computer based controller design model [8,9]. Ming Rao et. al. Used Kalman filters to design pressurized headbox [10]. Various design methods like bilinear control strategy are proposed in [11-29].

2. Mathematical Model of Headbox

In [30], described air cushioned head box's mathematical model in complete manner. This research uses the model described in [31] and it is expressed as,

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{0.528e^{(-0.6s)}}{(2.2s+1)} & \frac{(1.2539s+0.063)}{(30.051s^2+17.79s+1)} \\ \frac{(0.0205s+0.000149)e^{(-1.5s)}}{(43.6s^2+s)} & -\frac{(0.0007)e^{(-2s)}}{s} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \qquad (1)$$

Approximate model of headbox by considering important dynamics is expressed as:

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{0.528e^{(-0.6s)}}{2.2s+1} & \frac{0.081}{1.89s+1} \\ \frac{1.49\times10^{-4}e^{(-1.5s)}}{(43.6s^2+s)} & -\frac{-7.0\times10^{-4}e^{(-2s)}}{s} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \qquad (2)$$

$$G_{Headbox} = \begin{bmatrix} \frac{0.528e^{-0.6s}}{2.2s+1} & \frac{0.081}{1.89s+1} \\ \frac{1.49\times10^{-4}e^{-1.5s}}{(43.6s^2+s)} & -\frac{-7.0\times10^{-4}e^{-2s}}{s} \end{bmatrix} \qquad (3)$$

Where, pressure level in headbox is given by $y_1$and stock level in headbox is given by y_2. Speed of feed pump is given by $u_1$and position of air valve is given by u_2. Control variables are stock level and pressure. Manipulated variables are speed of feed pump and position of valve. Equation 1 to 3 represents the model of this process and it has four below mentioned elements.

$$g_{11} = \frac{0.528e^{-0.6s}}{2.2s+1}; g_{12} = \frac{0.081}{1.89s+1}; g_{21} = \frac{1.49\times10^{-4}e^{-1.5s}}{(43.6s^2+s)}; g_{22} = \frac{-7.0\times10^{-4}e^{-2s}}{s} \quad (4)$$

pressure of headbox to speed of feed pump is given by g_{11}, pressure of headbox to position of air valve is represented as g_{12}, stock level of headbox to speed of feed pump is given by g_{21} and stock level of headbox to position of air valve transfer functions is represented as g_{22}, where, pressure of headbox and stock level loop is represented by "g_{11}" and "g_{22}". while, disturbances to above mentioned loops are represented by "g_{12}" and "g_{21}".

In this paper, two methods are used to analyse and design controllers. Through controllers, decoupled headbox system is designed in the first method. Figure 3 shows the head box's decoupled Simulink model. Decouplers are designed using a static decoupling in this work, as mentioned below,

$D_1 = -0.1534 \text{and} D_2 = 0.2129$

As mentioned below, obtained decoupled models:

$$G_{11}(s) = \frac{-0.288s^2+0.882s+0.5452}{1.247s^3+5.365s^2+4.39s+1} \quad (5)$$

$$G_{11}(s) = \frac{5.421s^2+1.693s-7.229}{s(7500s^2+17500s \quad +10000} \quad (6)$$

Where, SISO Loop representing Pressure of head box is given by $G_{11}(s)$is Y1 – U1 and Loop representing Stock Level of headbox is given by G22(s) is Y2 – U2 SISO.

3. Proposed Methodology

Hybrid H-PSOABC algorithm is presented in this section. Artificial Bee Colony (ABC) Algorithm is combined with Particle Swarm Algorithm (PSO) to form a Hybrid PSOABC algorithm which tunes PID controller to enhance performance of optimization algorithm. Figure 2 shows the Hybrid H-PSOABC based PID tuning controller.

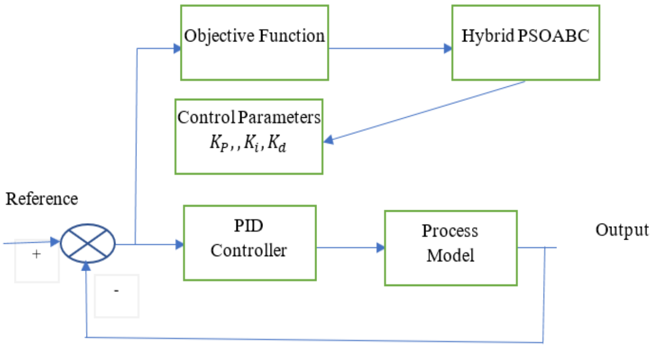

Fig. 2. Hybrid H-PSOABC-PID tuning of Controller's Schematic Diagram

4. ABC Algorithm

In [32], proposed an Artificial Bee Colony algorithm. There are three group of bees in artificial bee colony. They are scout, onlooker and employed. Position of food source as well as nectar amount of it shows the better solutions to the problem of optimization. Nectar value corresponds to fitness value and defines the solution's quality. In population, number of solutions equals the number of employed bees.

Generate the initial population in randomly distributed manner at the initial step. Food source position change are produced in the memory of employed bees and fitness value is measures at that position. The new position of the source will be stored if it had high value of nectar when compared to previous position and old position is replaced. Else old position is retained in the memory. New positions are examined by all employed bees and a better position receives more onlooker bees and position with less fitness value will receive few onlooker bees.

Positions are changed by onlooker bees and fitness value at that position are computed. In order to assess, positions are selected randomly by scout. Until reaching the criteria of termination, this process continuous. The employed bee is transformed into scout bee if its fitness value is showing any progress in the iterations.

In ABC algorithm, there are three parameters employed to control the process. They are food source count, maximum cycle number (MCN) and frontier value. Number of onlooker or employed bees equals number of food sources. Way in which best food sources utilized defines the efficiency and discovery of analysis and enhancement of bee colony.

In real time problems, best solutions are related to fast discovering solutions. Exploitation and exploration of search space should be done at least by one time in search process. In search space, exploitation is done by employed and onlookers bees in ABC algorithm whereas, exploration is done by scout bee.

Initialize the random population $(X_1, \dots, X_S)$. where, $X_i = \{x_{i1}, x_{i2}, \dots, x_{iD}\}$. Following expression is used t generate every solution vector,

$$x_{ij} = x_j^{min} + \left(x_j^{max} - x_j^{min}\right) \text{rand}\,[0,1] \qquad (7)$$

where, j = 1, 2,…, D; $i = 1, 2, \dots, w$,upper bounds of dimension j is represented as x_j^{max} and lower bounds of dimension j is represented as x_j^{min}.

In certain range of parameters $\overrightarrow{x_i}(i = 1, \dots\dots, w$,random solutions are produced in initial step of ABC. where, number of the food sources is represented as w.

New sources are computed by employed bees after that. Its quantity will equals half of total sources. New source v_{ij} is computed using equation (8).

$$v_{ij} = x_{ij} + \varphi_{ij}(x_{ij} - x_{kj}) \qquad (8)$$

where, uniformly distributed real random number is represented by φ_{ij} and it lies between [-1, 1], index of solution chosen randomly from colony is given by k, dimension of problem is given by D.Also that, if fitness of new food source is equal or better than that of X_i, new food source takes X_i in population and develop into a new member.

Based on probability given by (9), food sources are selected by scout bees in third step. After the generation of new food source, it is computed and functions with greedy selection. The determination of best food source is increased by employed bees.

$$P_i = \frac{fit_i}{\sum_{j=1}^{S} fitj} \qquad (9)$$

where, fitness of solution $\overrightarrow{x_i}$ is given by fit_i.

While considering nectar sources, prior knowledge and particulars are not employed by scout bees. Arbitrarily complete their search. With limit parameter, from employed bees, choose scout bees. A source is discarded, if it is not able understand with in specified trails. The bee corresponding to that source is a scout bee and it finds new food source. Limit parameter defines the number outgoing and incoming of a source. Equation (10) is used by scout bee to compute new food source.

$$x_{ij} = x_j^{min} + \left(x_j^{max} - x_j^{min}\right) * \text{rand} \qquad (10)$$

New food source is computed by employed bees depends on above equation by searching in current food source's neighbourhoods.

In operation of ABC, onlooker and employed bees are used and in exploration scout bees are used. To nest, maximum food quantity is brought by bees. In the problem of maximization, objective function $F(\theta_i)$ is maximized. where, $\theta_i \in R^p$ and it represents the ith source position. In source, nectar amount is given by $F(\theta_i)$. Population of source is given by $P(c) = |\theta_i(c)|, i = 1, 2, \dots, S$, it includes, all source's position.

The selection probability of a source depends on its nectar amount. High nectar amount corresponds to high selection probability and it is given by,

$$P_i = \frac{F(\theta_i)}{\sum_{k=1}^{S} F(\theta_k)} \qquad (11)$$

Where, different from is given by $\theta_k(c)$.In population they are randomly formed indices.

The source with quality is selected by onlooker bees, after observing employed bee's dance.

Neighbouring source and its nectar values are identified. Following equation is used to compute the neighbour's position information.

$$(c+1) = \theta_i(c) \pm \phi(c) \qquad (12)$$

where, difference of parts of $\theta_i(c)$and $\theta_k(c)$ is given by $\phi(c)$.

Bee moves to its beehive and shares this data with further bees, if nectaramount of$\theta_i(c+1)$, F(θ_i (c+1)), is greater than nectar amount in position $\theta_i(c)$and it remain $\theta_i(c+1)$ in mind as a new position. In mind it goes on observance $\theta_i(c)$ if not. If limit parameter is not bale to understand theposition θ_i of nectar source, then it is a redundant source. Scout bees are formed by bees corresponding to that redundant source.

Random research is created by scout bee. New sources are identified by this and θ_i is assigned to them. For preferred number of cycles, the algorithm iterates. Variable's possible values are denoted by best nectar of sources. For objective function, solution is denoted by computed amount of nectar.

Particle Swarm Optimization

Kennedy and Eberhart (1995) developed PSO. Social behavior of a collection of migrating birds is motivated to form PSO algorithm. Bird in flock corresponds to a solution in PSO and it is termed as particle. In Genetic Algorithms (GAs), chromosome corresponds to particle. From parent birds, new birds are not produced by PSO as in GA. Social behaviour of birds are developed instead. Because of this destination is reached by particles.

Collection of random particle N is used to initiate the process. In S-dimensional space, points are used to represent ith particle's position. Number of variable is given by S. Flying velocity (V_i), best position it arrived in previous cycles (P_i) and current position (X_i) are the three parameters observed by every particle i. They are given by,

$$\begin{array}{l} \text{Current position } X_i = (x_{i1}, x_{i2}, \dots, x_{iS}) \\ \text{Best previous position } P_i = (p_{i1}, p_{i2}, \dots, p_{iS}) \\ \text{Velocity of flying} V_i = (v_{i1}, v_{i2}, \dots, v_{iS} \end{array} \qquad (13)$$

Position (P_g) of best particle (g) is calculated inevery time interval (cycle) and it is the best fitness of all particles.

In order get close to best particle g,velocity$V_i$is updated by every particle as,

$$\text{New } V_i = \omega \times \text{current } V_i + c_1 \times \text{rand}() \times (P_i - X_i) + c_2 \times \text{Rand}() \times (P_i - X_i) \qquad (14)$$

Particle's updated position uses new velocity $V_i$and it becomes:

$$\text{New position } X_i = \text{current position } X_i + \text{ New } V_i$$

$$V_{max} \geq V_i \geq -V_{max} \qquad (15)$$

Where, two positive constants are given by c_1 and $c_2$and they are termed as learning factors ($c_1 = c_2 = 2$); two random functions are represented as rand ( ) and Rand ( ) and they lies between [0, 1], an upper limit on maximum change of particle velocity is given by V_{max}, and inertia weight is given by ω and it is used as an enhancement to manage influence of previous history of velocities on current velocity. The local and global search are balanced by operator ω and its value decreases linearly from 1.4–0.5 with respect to time. With large weight, global search is initiated and local search is favoured with reduced value.

In equation (15), cognition is represented by second term. It is also termed as private judgement of a particle. It is computed by comparing best and current position of a particle. Between particles, social collaboration is represented by third in that equation. It is also computed based on best and current position of a particle. User specified velocity value V_{max} is used to limit the particle's velocity change between lower and upper bound. Particle flies to new position, if its new position is computed using equation (6). Size of population, generation cycle number, particle's maximum velocity change V_{max} and ω are the major parameters of PSO.

1.1.1. Proposed H-PSOABC Process for tuning the PID Controller

Initial Path for ABC is given by H-PSOABC algorithm, ABC algorithm run until reaching maximum number of iteration which is a stooping criteria of the algorithm in this hybridization method. ABC algorithm produces, optimum values for individual and for PSO these values are given in initial point. Initial points are randomly generated by ABC in normal cases. But here it is given by hybridization. ABC generates the final values.

Proposed PSOABC and agent-based algorithm for tuning of PID Controller

Following steps are used to perform the ABC algorithm:

Step 1: Source and destination nodes are selected and path set between these source and destination nodes are established by applying forward and reverse agent.

H-PSOABC is initialized

Initial population $X_i; i = 1,2,\ldots\ldots, SN$ is generated

In PSO, half part of bees are selected as employed bee

Step 2: To get Pi, particles are computed and best $\theta_k(c)$is selected as Pi. For population fitness is computed.

Step 3: Compute a new one using a iteration formulas of ABC.

For every employed bee Do

For synthetic QoS, new solution V_i is produced

For synthetic QoS, f_i value is computed

Greedy selection process is applied

For solutionsX_i, probability values pi are computed

For every onlooker bee

Based on pi, solution X_i is selected

New solution V_i is produced

Greedy selection process is applied to compute f_i

If scout has abandoned solution, then replace new solution replaces it and randomly it will be produced

Best solution is memorized

Step 4: Tuning parameter is replaced by P_i, if it is better. Best P_i is replaces $\theta_k(c)$, if it is better.

Step 5: Stop the algorithm, if iteration time goes beyond the predefined value, else go to step 3.

Step 6: Value is computed and routing table is modified.

cycle -> cycle + 1

until cycle->MCN

PID controller's gain is computed using H-PSOABC algorithm$(k_p, k_i and k_d)$. Next section discusses about design of PID controller using H-PSOABC and other methods.

5. Controller Design

H-PSOABC algorithm is used in this work to design a PID controller. The performance designed H-PSOABC- PID controller is compared with Zeigler – Nichols design of PID controller and Tyreus – Luyben tuning based PID controller [34]. PID controller's standard form is given by,

$$C(s) = K_p(1 + \frac{1}{\tau_I s} + \tau_D s) \qquad (16)$$

And

$$C(s) = K_p + \frac{K_I}{s} + K_D s \qquad (17)$$

Where, proportional gain is given byK_p, integral time is represented as $\tau_I$and derivative time constant is given by τ_D, integral gain is represented as $K_I = \frac{K_p}{\tau_I}$and derivative gain of controller is given by $K_D = K_p \tau_D$.

Gain of PID controller is computed using PSOABC method. Important parameters of both models are used in bating parameters of controller in ZN and TL methods. Using PSOABC, PID controller's optimized parameters are computed. Table 1 shows the computed parameter values by ZN and TL methods.

TABLE 1: TUNING VALUES OF CONTROLLER

Loop	**Controller**	K_p	K_i	K_d
Pressure	**H-PSOABC**	7.20	2.70	2.41
	ZN	9.79	12.09	1.98
	TL	5.10	1.43	1.31
Stock level	**H-PSOABC**	-714.10	-0.70	-433.20
	ZN	-839.37	-269.85	-652.71
	TL	-437.17	-31.94	-431.69

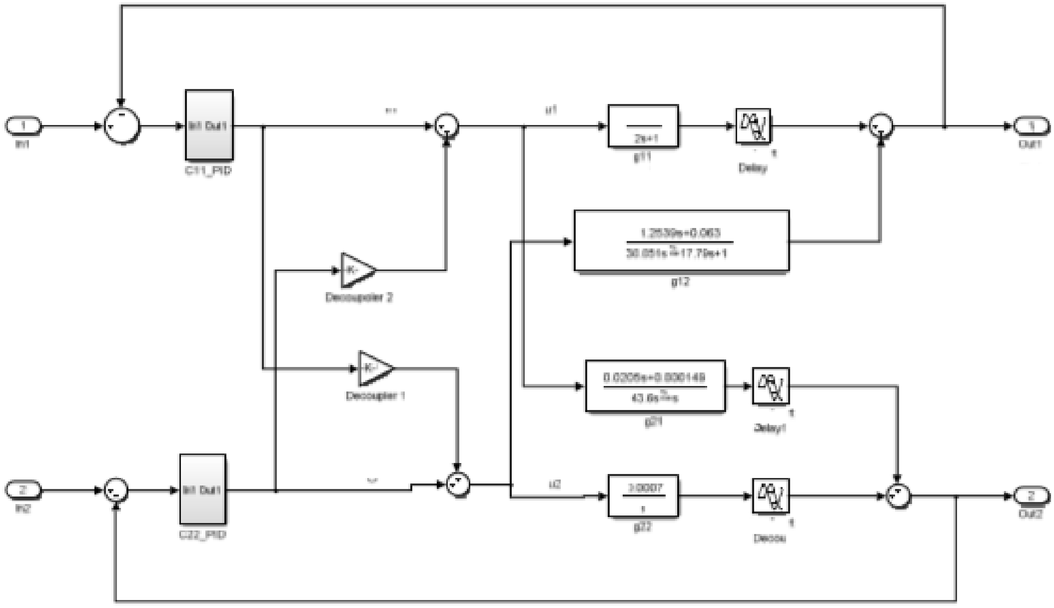

Fig. 3. Headbox's Decoupled Simulink Model

Table 1 shows tuning values of controller design. Using MATLAB – SIMULINK,these tuning values are applied to both model types. Figure 3 shows the decoupled headbox system's Simulink model. In multivariable system, any type of loop interaction is avoided using this decoupling. For a given paper headbox system, SISO models are obtained using static decoupling. The procedure for obtaining static decoupling values are as follows,

De-coupler 1 = -0.1534 De-coupler 2 = 0.2129

Figure 4 and Figure 5 shows the and Headbox Stock Level and Headbox pressure level's SISO loops.

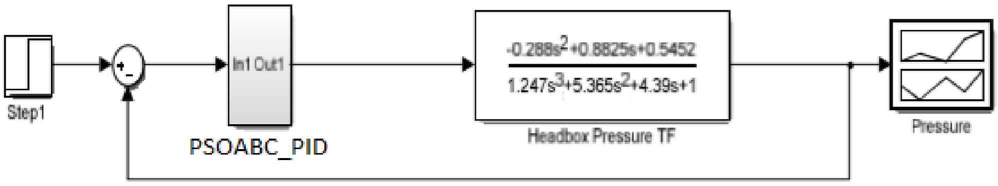

Figure 4: Headbox Pressure's SISO Simulink Model

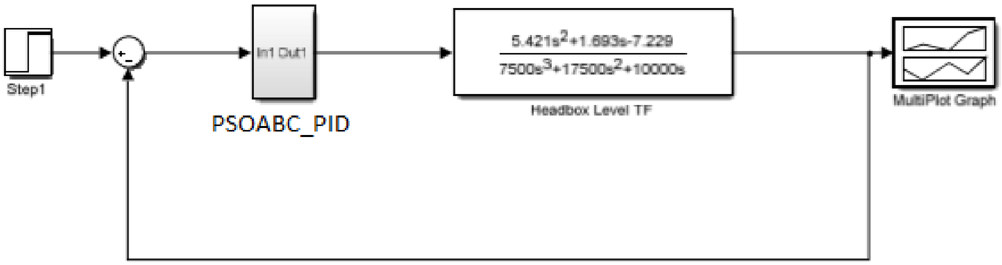

Figure 5. **Headbox** Stock Level's SISO Simulink Model

6. Result Analysis

Performance of paper machine head box design are analysed in this section. For a given system without controller and with frequency response, open loop bode plots of stock level and headbox pressure model are shown in figure 6 and figure 7. Table 3 shows phase margin and gain values of both models.

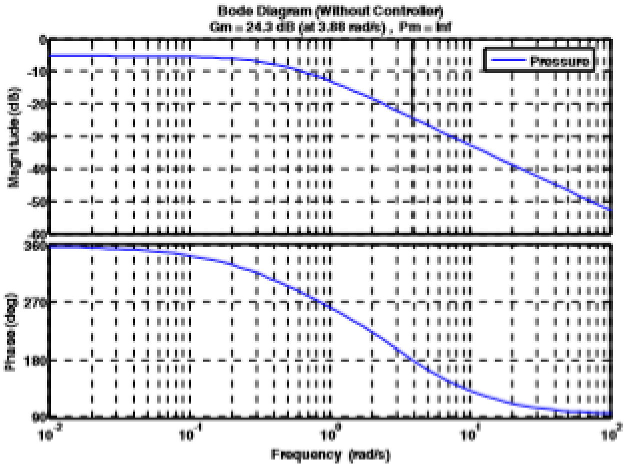

Figure. 6. Pressure Loop (SISO)'s Bode Plot of

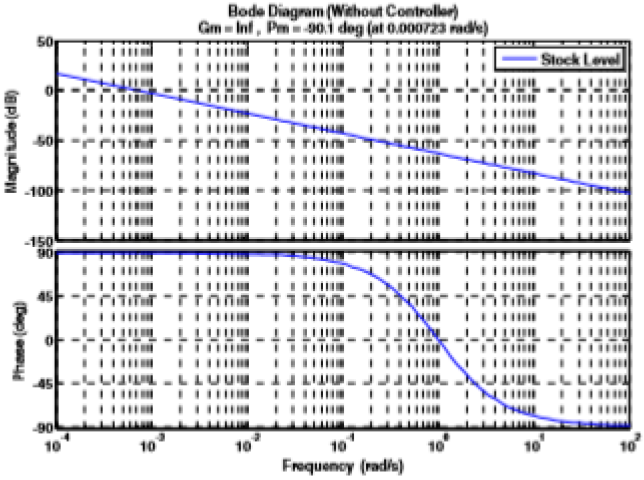

Figure. 7. Stock Level Loop (SISO)'s Bode Plot

TABLE 2: FREQUENCY RESPONSE OF SISO MODEL

Loop	**Gain Margin (in dB)**	**Phase Margin (in degree)**
Pressure	244	Infinite
Stock Level	Infinite	-90 (unstable)

Figure 8 and figure 9 shows the open loop bode plot of controllers with both loops. In this paper, H-PSOABC – PID controller responses are illustrated in order to limit data. But presented the response's statistical value and all tuning methods of controller are described.

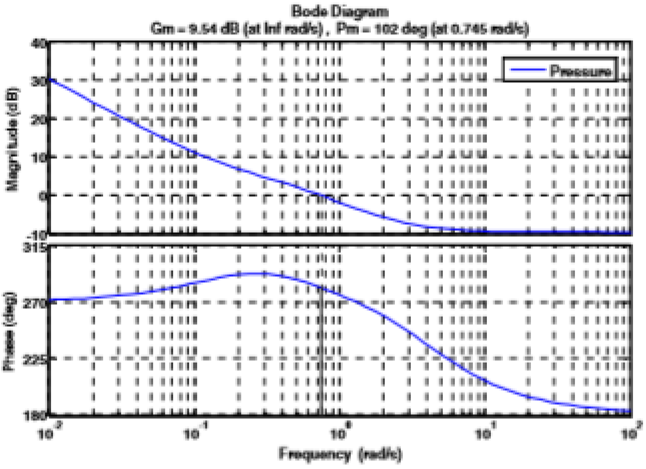

Figure. 8. H-PSOABC Controlled Pressure Loop (SISO)'s Bode Plot of

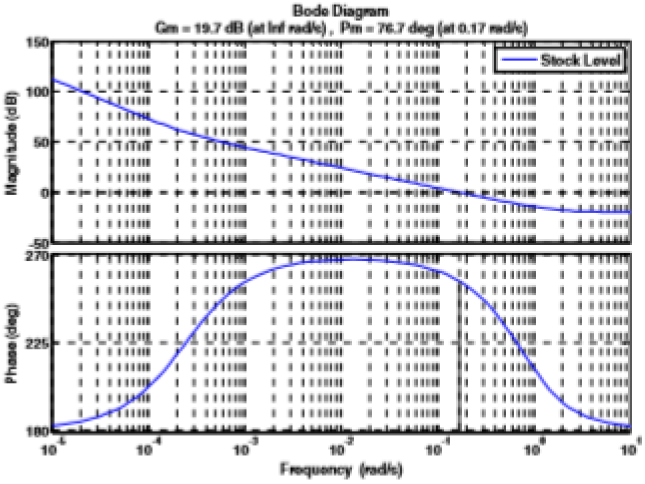

Figure. 9. H-PSOABC Controlled Stock Level Loop (SISO)'s Bode Plot

TABLE 3: PERFORMANCE INDICES COMPARISON OF DECOUPLED AND PRESSURE LOOP (SISO)

Performance Indices	**Pressure Loop (SISO)**				**Pressure Loop (DECOUPLED)**			
	H-PSOABC	**PSO**	**ZN**	**TL**	**H-PSOABC**	**PSO**	**ZN**	**TL**
ITSE	0.06	0.08	0.29	2.57	0.02	0.03	0.06	0.14
ITAE	0.29	0.32	0.99	2.65	0.40	0.46	0.71	2.73
IAE	0.60	0.66	1.05	1.28	0.31	0.36	0.55	0.90
ISE	0.56	0.64	0.77	0.69	0.12	0.17	0.26	0.31

TABLE 4: PERFORMANCE INDICES COMPARIOSN OF DECOUPLED AND STOCK LEVEL LOOP (SISO)

Performance Indices	**Stock Level(SISO)**				**Stock LevelLoop (DECOUPLED)**			
	H-PSOABC	**PSO**	**ZN**	**TL**	**H-PSOABC**	**PSO**	**ZN**	**TL**
ITSE	1.63	1.94	7.96	6.71	1.02	1.22	2.07	2.05
ITAE	12.95	13.42	27.01	51.61	12.03	12.64	15.13	33.98
IAE	3.01	3.36	5.23	5.49	1.98	2.73	2.82	3.25
ISE	1.91	2.11	3.45	2.57	0.65	0.91	1.02	1.02

Table 3 and table 4 shows the experimental results of decoupled system and SISO model.

7. Conclusion

In all aspects, optimal results are produced by using H-PSOABC technique as shown from obtained experimental results. Performance indices, frequency response and time response parameters are used to compare the controller performances. Robust as well as better performances are shown by the presented H-PSOABC-PID in all aspects. Efficient results in all aspects can be obtained by using a optimization techniques in future.

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