A New Implicit Self-Tuning PID Pole-Placement Control Incorporating Feed-Forward/Feedback Compensator

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Abstract:

This paper presents the derivation of a new computationally efficient self-tuning controller with a proportional plus integral plus derivative (PID) structure which incorporate the effectiveness the Feed forward Feedback (FF-FB) control. The main feature of the proposed design is a combination of the advantages of implicit self-tuning property, in which the controller parameters tuned automatically on-line, with those of PID and Pole placement control. It is an implicit algorithm, in the sense that the

controller step is trivial and avoids solving simultaneous equations (as is the case in the most of the adaptive pole-placement controllers which involve solving a Diophantine Equations at each sampling step). It tracks set-point changes with the desired speed of response. Additionally, at steady state, the controller has the ability to regulate the measured disturbance to zero. Example simulation results using simulated real plant model (Liquid Temperature Control in a Stirred Tank System) demonstrate the effectiveness of the proposed controller compared to conventional PID controller.

Keywords: implicit self-tuning control, PID control, pole-placement control, temperature control and feed-forward feedback control.

1. Introduction:

It is well known fact, that three-term conventional PID control algorithm remains the most popular approach for industrial process control despite continual advances in the control theory. This is not only due to its simple structure which is conceptually ease to understand and, which makes manual tuning is possible, but also to the fact the algorithm provides adequate performance in the vast majority of applications. However, in spite of the outlined advantages of conventional PID controllers, they need to be retuned if the presses to be controlled is subjected to significant changes in order to achieve optimum performance. For this reason, many adaptive PID control designs have been proposed, e.g. [1, 2, 3, 4, 5].

However, most of self-tuning based PID control designs (see for Example [1, 2, 6, 7]), in which the tuning parameters must be selected using a trial and error procedure. One way to overcome this problem is to combine the advantages of PID with those of pole-placement control (see for instance [3, 4, 5, 8, 9]).

The popularity of pole-placement techniques may be attributed to that in the regulator case they provide mechanism to over-come the restriction to minimum-phase processes. In addition, in the servo case, they provide the ability to directly introduce bandwidth and damping ratio as tuning parameters. Besides, there is some improvement in robustness of pole-placement methods, as they simply modify the system dynamics as opposed to canceling them as per the early optimal self-tuning controllers. Furthermore, unlike many of the self-tuning based PID control design (see for example [1, 2, 6, 7]), in which the tuning parameters must be selected using a trial and error procedure, the tuning parameters for pole-placement controllers can be automatically set on-line by specifying the desired closed loop poles. However, most of pole-placement controllers involve solving Diophantine Equations which may cause numerical instability [3, 5, 8, 9].

In industrial processes, the disturbance input introduces error in the system performance. In several systems the disturbance can be predicted and its effect can be eliminated with the help of feed forward controller before it can change output of the system. The main reason for involving the feed forward compensator in practical application is for, optimization and to ensure zero steady state error [10] . Also, in some cases the feed-forward feed-back control design can be used to avoid obstacles of integral wind up which may be caused by using PID control.

Therefore, in an attempt to obtain a robust design, a new implicit adaptive PID pole-placement controller which avoids solving Diophantine Equations and incorporates Feed-Forward/Feedback compensator is proposed. This work is based on the previous works of Sirisena and Teng [11] and Zayed et al. [4, 10, 12].

The paper is organized as follows: Section (2) presents the mathematical modeling of Jacketed Stirred-Tank Heater**,** the derivation of the control law is shown in section (3). In section (4), simulation case study is carried out in order to demonstrate the effectiveness of the proposed controller in the performance of the closed loop system. Finally, some concluding remarks for future are presented in section (5).

2. Mathematical Modeling of Stirred-Tank Heater (jacket model)

Consider the jacketed stirred-tank heater shown in (Fig. 1). A hot fluid circulated through the jacket (which is assumed to be perfectly mixed), and flow between the jacket and vessel increases the energy content of the vessel fluid. The rate of heat transfer from the jacket fluid to the vessel fluid is [13, 14]:

$$Q' = UA'^{[T_j - T_{to}]} \qquad (1a)$$

$$A' = Л(r_2{}^2 - r_1{}^2) \qquad (1b)$$

Where: U is the overall heat transfer coefficient, Q' is the rate of heat per unit of time and A' is the area for heat transfer (between tank and jacket). Assuming that the volume and density are constant, $F_i = F_o$. Where F_i is inlet volumetric flow rate and F_o is outlet volumetric flow rate. [13,14]. Whereas, $r_1$and r_2 are the radiuses of the thank the jacket, respectively.

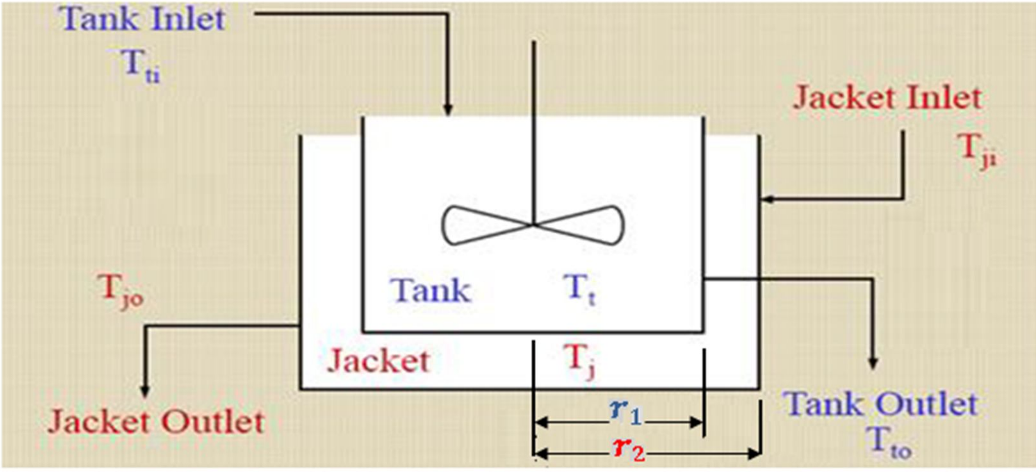

Fig.(1): The stirred-Tank heater (jacket model)

Energy balances on the vessel and jacket fluids result in the following equations:

$$\frac{dT_t}{dt} = \frac{F_t}{V_t}(T_{ti} - T_{to}) + \frac{UA'}{\rho_t V_t C_{pt}}(T_{jin} - T_{to}) = f_1(T_{to}, T_{jo}, F_j, F_t, T_{ti}, T_{jin}) \qquad (2)$$

$$\frac{dT_j}{dt} = \frac{F_j}{V_j}(T_{jin} - T_{jo}) + \frac{UA'}{\rho_j V_j C_{pj}}(T_j - T_t) = f_2(T_{to}, T_{jo}, F_j, F_t, T_{ti}, T_{jin}) \qquad (3)$$

Where: $f_1(T_{to}, T_{jo}, F_j, F_t, T_{ti}, T_{jin})$ and $f_2(T_{to}, T_{jo}, F_j, F_t, T_{ti}, T_{jin})$ are functions which depend on $(T_{to}, T_{jo}, F_j, F_t, T_{ti}$ and $T_{jin})$. Here T_{to} is the tank outlet temperature, T_{ti} is the tank inlet temperature, $T_{jo}$is the jacket outlet temperature, F_j is the jacket volumetric flow rate F_t is the tank volumetric flow rate and T_{jin} is the jacket inlet temperature. In this case study the outputs are the vessel and jacket temperatures, which are also the states. Whereas, the inputs are the jacket flow rate, feed flow rate, feed temperature, and jacket inlet temperature. If the outputs, states, and inputs, in deviation variable form, are:

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} T_{to} - T_{tos} \\ T_{jo} - T_{jos} \end{bmatrix}$$

$$u = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} F_j - F_{js} \\ F_t - F_{ts} \\ T_{ti} - T_{tis} \\ T_{jin} - T_{jins} \end{bmatrix} \tag{4}$$

Then, the linearized model can be expressed as [13]:

$$\boldsymbol{A} = \begin{bmatrix} -\frac{F_s}{V} - \frac{UA'}{\rho V C_p} & \frac{UA'}{\rho V C_p} \\ \frac{UA'}{\rho_j V_j C_{pj}} & -\frac{F_{js}}{V_j} - \frac{UA'}{\rho_j V_j C_{pj}} \end{bmatrix} \tag{5}$$

$$\boldsymbol{B} = \begin{bmatrix} 0 & \frac{T_{jins} - T_{js}}{V_j} & \frac{F_{ts}}{V_t} & 0 \\ \frac{T_{jins} - T_{js}}{V_j} & 0 & 0 & \frac{F_{js}}{V_j} \end{bmatrix} \tag{6}$$

$$\boldsymbol{C} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \& \quad \boldsymbol{D} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{7}$$

Where the subscript *s* is used to indicate a steady-state value $(T_{tos}, T_{js}, T_{is}, T_{jins}, F_s)$.

If the process parameters and steady-state values are considered as [13]:

Table 1. Parameters and steady-state values

$F_{ts} = 1\ (ft^3)/min$	$T_{is} = 50F^o$	$T_{jis} = 200\ F^o$
$\rho C_p = 61.3\ Btu/(F^o.ft^3)$	$T_{tos} = 125F^o$	$T_{js} = 150\ F^o$
$\rho_j C_{pj} = 61.3\ Btu/(F^o.ft^3)$	$V_t = 10\ ft^3$	$V_j = 2.5\ ft^3$
$UA' = 183.9\ Btu/(F^o.min)$	$F_{js} = 1.5\ ft^3/min$	

And by selecting the sampling time $T_s = 3$ sec , the linear discrete model is then obtained using (table.1) as:

$$y(t) = \frac{z^{-1}(0.19856 + 0.035284z^{-1})}{1 - 0.63872z^{-1} + 0.0024788z^{-2}}u(t) + \frac{1}{1 - 0.63872z^{-1} + 0.0024788z^{-2}}\xi(t) + \frac{0.48781z^{-1}(1 - 0.3608z^{-1})}{1 - 0.63872z^{-1} + 0.0024788z^{-2}}d(t) \quad (8)$$

a) the transfer function between the T_{to} and T_{ji} is:

$$G_p(z^{-1}) = \frac{z^{-1}(0.19856 + 0.035284z^{-1})}{1 - 0.63872z^{-1} + 0.0024788z^{-2}} \quad (9)$$

b) The transfer function between the T_{to} and T_{ti} is:

$$G_d(z^{-1}) = \frac{0.48781z^{-1}(1 - 0.3608z^{-1})}{1 - 0.63872z^{-1} + 0.0024788z^{-2}} \quad (10)$$

3. Derivation of Control Law:

In deriving the implicit PID pole-placement control incorporating feed-forward feedback compensator control law, the process model considered in this work is a linear generalized Auto-Regressive Moving Average (GARMA) model of the form [1, 2, 3, 4]:

$$A(z^{-1})y(t) = z^{-k}B(z^{-1})u(t) + C(z^{-1})\xi(t) + z^{-k}D(z^{-1})d(t) \tag{11}$$

Where $y(t)$ is the measured output, $u(t)$ is the control input, $\xi(t)$ is an uncorrelated sequence of random variables with zero mean and $d(t)$ is the measured disturbance. k is the time delay in the integer sample interval and (t) denotes the sampling instant, t= 1, 2, 3… The polynomials $A(z^{-1})$, $B(z^{-1})$, $C(z^{-1})$ and $D(z^{-1})$ are expressed in terms of the backward shift operator, z^{-1}\{ i.e. $z^{-1}x(t) = x(t-1)$\} are given. As [1- 4]:

$$\left.\begin{aligned} A(z^{-1}) &= 1 + a_1z^{-1} + a_2z^{-2} \ldots\ldots, \ldots\ldots a_{n_a} z^{-n_a} \\ B(z^{-1}) &= b_o + b_1z^{-1} + b_2z^{-2} \ldots\ldots, \ldots\ldots b_{n_a} z^{-n_a} \quad , b_o \neq 0 \\ C(z^{-1}) &= 1 + c_1z^{-1} + c_2z^{-2} \ldots\ldots, \ldots\ldots C_{n_c} z^{-n_c} \\ D(z^{-1}) &= 1 + d_1z^{-1} + d_2z^{-2} \ldots\ldots, \ldots\ldots d_{n_d} z^{-n_d} \end{aligned}\right\} \tag{12}$$

Where n_a , n_b, n_c and n_d are the degree of the polynomials $A(z^{-1})$, $B(z^{-1})$, $C(z^{-1})$ and $D(z^{-1})$ respectively and $b_o \neq 0$. It is father assumed that all roots of $C(z^{-1})$lie inside the unit disc.

The control law is assumed to be:

$$u(t) = \frac{[Rw(t) - (F)y(t) + H_d d(t)]}{Q} \tag{13}$$

Where $w(t)$ is the set point and $Q\ (z^{-1}), R\ (z^{-1})$ and $H_d(z^{-1})$ are user-defined transfer functions expressed in the backward shift operation z^{-1}.

If we set:

$$R\ = vH_0 \tag{14}$$

and set the transfer function $Q\ (z^{-1})$ such that the following relation is satisfied [1-4]:

$$Q = \frac{\Delta q}{v} \tag{15}$$

Then equation (15) becomes:

$$u(t) = \frac{[vH_0 w(t) - vFy(t) + vH_d d(t)]}{\Delta q} \tag{16}$$

Where $\Delta = 1 - z^{-1}$ is the difference operator, q is a pole placement compensator, H_0 is tracking user-defined transfer function, H_d is feed forward compensator and v is a user-fined gain. It can be seen from equation (16) that the control action can be considered to be a Feed forward/feedback controller.

3.1 Self-tuning Discrete PID Controller

The most commonly used velocity form [1, 2, 3,4, 12] as:

$$\Delta u(t) = (K_I)v\, w(t) - [K_P + K_I + K_D]y(t) - [-K_P - 2K_D]y(t-1) - K_D y(t-2) \tag{17}$$

If we assume that the degree of F is equal to 2 and set:

$$q = 1 \text{ and } H_0 = F(z^{-1})|_{z=1} = F(1),\ \ H_d = 0 \qquad (18)$$

and make use of (17), (18) and (16), yields a linear self-tuning controller with PID structure [1, 2, 3 4,13 15 ,16]:

$$\Delta u(t) = vF(1)w(t) - vFy(t) \qquad (19)$$

$$K_P = -v(f_1 + 2f_2) \qquad (20)$$

$$K_I = v(f_0 + f_1 + 2f_2) \qquad (21)$$

$$K_D = v(f_2) \qquad (22)$$

It can also clearly be seen from equations (19), (20), (21) and (22) that, the order of F which indicates the type of the controller (PI or PID), is governed by the polynomial $A\ (z^{-1})$. If the polynomial F is of first order then a PI controller is obtained. A PID controller occurs if F is of second order. The controller is tuned by a selection of the gain v. However, the main disadvantage of many PID self-tuning based controllers is that the tuning parameters must be selected using a trial and error procedure. Alternatively, these tuning parameters can be automatically and implicitly set on line by specifying desired closed loop poles [4, 5, 8, 12].

3.2 New Implicit Self-tuning PID Pole-Placement Controller incorporating Feed forward/feedback Compensator

The control law given by equation (16) can be written as:

$$u(t) = \frac{[vH_0w(t) - v(F)y(t) + vH_d d(t)]}{\overline{q}} \qquad (23)$$

Where:

$$\overline{q} = \Delta q \qquad (24)$$

Combining equations (23) and (11), the closed loop transfer function is obtained as[4, 12]:

$$y(t) = \left[\frac{z^{-k} v H_0 B w(t)}{(A\overline{q} + z^{-k} v B F)}\right] + \left[\frac{\Delta q C \xi(t)}{(A\overline{q} + z^{-k} v B F)}\right] + \left[\frac{z^{-k}(v H_d \bar{B} + D\overline{q}) d(t)}{(A\overline{q} + z^{-k} v B F)}\right] \qquad (25)$$

If we set:

$$F(z^{-1}) = A(z^{-1}) \qquad (26)$$

Then equation (25) becomes:

$$y(t) = \left[\frac{z^{-k} v H_0 B w(t)}{A(\overline{q} + z^{-k} v B)}\right] + \left[\frac{\overline{q} C \xi(t)}{A(\overline{q} + z^{-k} v B)}\right] + \left[\frac{z^{-k}(v H_d B + D\overline{q}) d(t)}{A(\overline{q} + z^{-k} v B)}\right] \qquad (27)$$

It can also clearly be seen from (26) that the order of F which indicates the type of the controller (PI or PID), is governed by the polynomial $A(z^{-1})$. The desired closed loop is achieved by using $\overline{q}$ such that the:

$$(\overline{q} + z^{-k} v B) = K' T C \qquad (28)$$

Where T represents the desired closed loop poles.

The above condition can be achieved by selecting T such that [13]:

$$T(z^{-1}) = \left(1 + t_1 + \cdots + t_{n_t}\right)^{-1} \left(1 + t_1 z^{-1} + t_2 z^{-2} + \cdots + t_{n_t} z^{-n_t}\right) \quad (29)$$

Here K' is a user-defined gain that has to be chosen such that the steady state error is zero . It can be seen form equations (23), (24) and (28) that the user-defined gain K' is employed to ensure the incorporation of the integral action into the design (i.e. $\overline{q}(1)$ in equation (23) equal to zero) [4, 11, 12].

Where n_t represent the degree of the polynomial T Equation (28) can be expressed as:

$$\overline{q} = K'TC - z^{-k}vB \qquad (30)$$

It can be seen from equations (30) and (29) that in order to ensure that $\overline{q}'$ involves the deference operator (Δ), we set:

$$K' = \frac{vB(1)}{C(1)} \qquad (31)$$

Where H_0 is a user-defined polynomial. In servo case, the Zero steady state error can simply be achieved by setting:

$$H_0(z^{-1}) = F(z^{-1}) = A(z^{-1}) \qquad (32)$$

The closed loop system given by equation (27) then becomes:

$$y(t) = \left[\frac{z^{-k}vABw(t)}{A(\overline{q} + z^{-k}vB)}\right] + \left[\frac{\overline{q}C\xi(t)}{A(\overline{q} + z^{-k}vB)}\right] + \left[\frac{z^{-k}(H_dB + D\overline{q})d(t)}{A(\overline{q} + z^{-k}vB)}\right] \quad (33)$$

In regulating case, the zero steady state error is ensured by setting the feed forward compensator as:

$$H_d = -\frac{D(1)\overline{q}(1)}{vB(1)} \quad (34)$$

Using equations (31), (32), (34) and (23) yields the corresponding control signal:

$$u(t) = \frac{v[Aw(t) - Ay(t) + H_d d(t)]}{\overline{q}} \quad (35)$$

In order to show the inherent incorporation of the PID control explicitly in our design, the polynomial $\overline{q}$ must be split into an integral action (Δ) part and pole-placement compensator part. We can easily compute q' from equation, $\overline{q} = \Delta q$ as follows:

$$\left.\begin{aligned} q_0 &= \overline{q}_0 \\ q_i &= \textstyle\sum_{j=0}^{i} \overline{q}_j \end{aligned}\right\} \quad (36)$$

The proposed control law given by equation (35) with process is shown in (Fig.2).

Note that as stated earlier, the controller is termed 'Implicit ' in the sense that it does not require a solution of the Diophantine Equation (as is done in the explicit case).

3.2.1 New Self-Tuning Implicit PID pole-placement Controller Feed Forward/Feedback Algorithm Summary

The algorithm for the pole-placement controller can then be summarized as follows:

Step 1. Select the desired closed-loop system poles placement polynomial, $T(z^{-1})$, and selected the gain v.

Step 2. Read the new values of $y(t)$, $u(t)$ and estimation of the process parameters $\hat{A}$, $\hat{B}$,$\hat{C}$and $\hat{D}$ using the RLS algorithm.

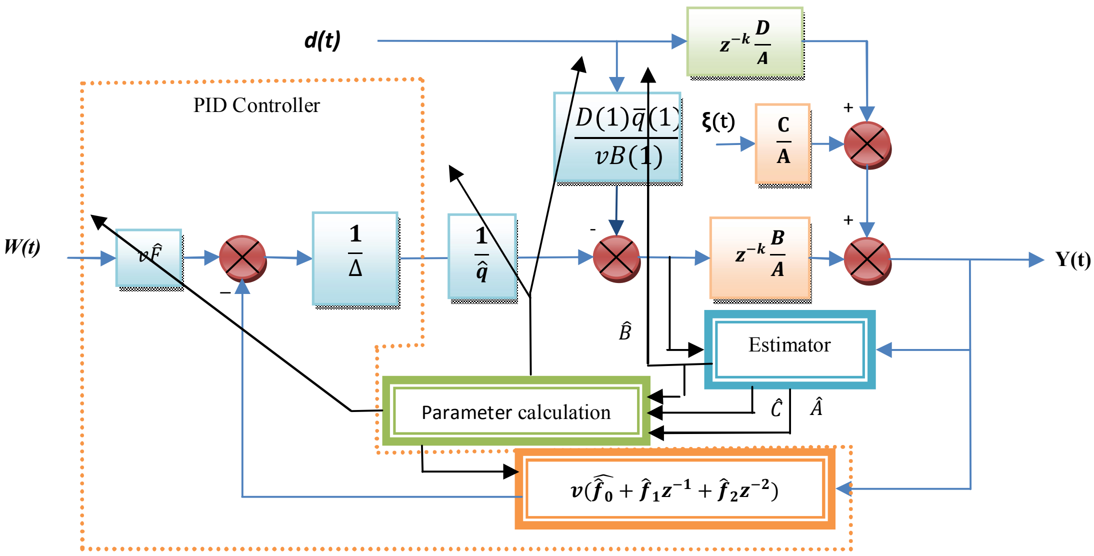

Fig.(2): Feed Forward/Feedback PID Pole-Placement Self-Tuning Controller

Step 4. Set $\hat{F}(z^{-1}) = \hat{A}(z^{-1})$

Step 5. Compute K' using equation (31), compute $\hat{\bar{q}}$ using equation (30) and compute H_0 using equations (32), respectively.

Step 6. Apply the control law using equation (23).

Steps 2 to 6 are repeated for every sampling instant.

4. Simulation Results:

The new implicit self-tuning PID pole-placement incorporating Forward/Feedback compensator is applied to the jacketed stirred-tank heater discussed in section (2), in order to demonstrate the effectiveness of the proposed controller in the performance of the closed loop system. In order to implement the implicit controller, the implementation steps summarized in section (3) are followed.

Note that, as discussed in section (3), in this case-study, the PID structure controller is obtained since the polynomial $A(z^{-1})$ is of order two. The simulation were performed over 600 samples under set point changes from 30C° to 70 C° and from 70C° to 30 C° every 100 sampling instants. The user-defined gain were selected as follows: *v=2.*

4.1 Investigating the Influence of the set point and load disturbance on the closed-loop system:

The desired closed loop poles polynomial T was constant as: $T = 1 - 0.5z^{-1}$. In order compare the performance of the proposed design with that of conventional PID control, this simulation experiment was arranged such that in the first 300 samples the proposed design is used, whereas the conventional PID controller is used in the last 300 samples. Also, in order to see the influence of the load disturbance on the closed loop system response, an artificial load disturbance of value of $10.5^0\mathrm{C}$ (15% of set-point) was added to the output of the closed loop system from 50th sampling instant to 600th sampling time instant. The output and the control input are respectively shown in Fig.(3a) and Fig.(3b).

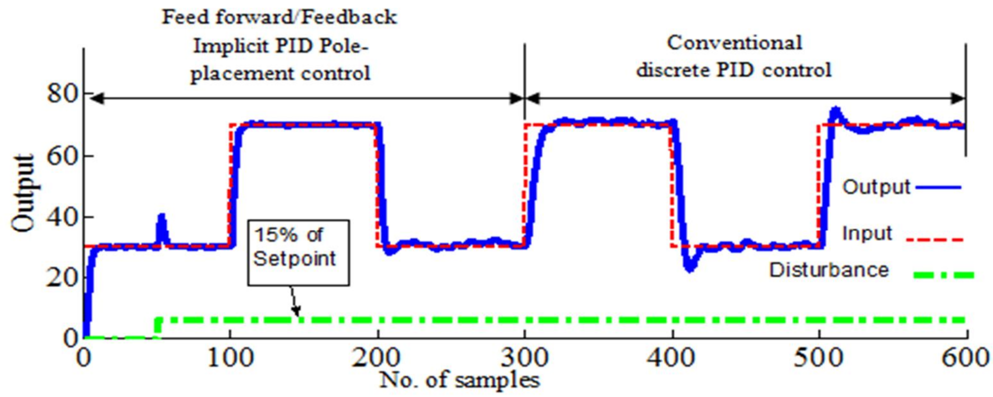

Fig.(3a): The output

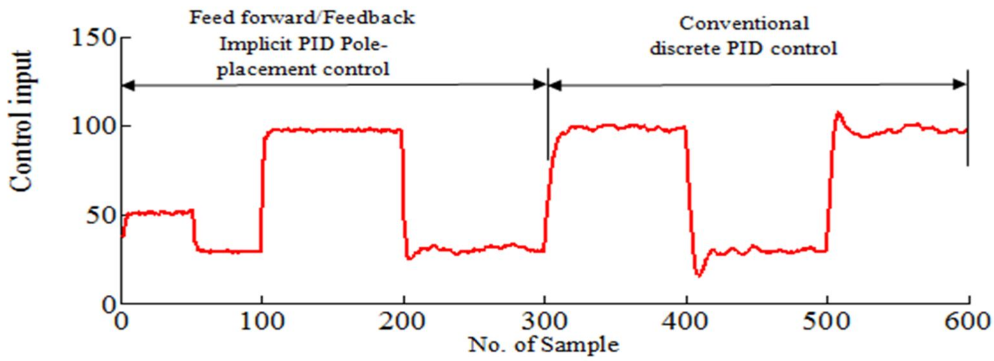

Fig.(3b): The control input

It can clearly be seen from the Fig.(3a) and Fig.(3b) that the desired output is achieved in the case where the implicit PID pole placement incorporating feed-forward feedback compensator is used. Whereas, undesired oscillations in the control input and closed loop output are resulted when the conventional PID is employed. It can also be seen from Fig.(3a) and Fig.(3b) that the proposed design has the ability to track the set point change and place the closed loop poles at pre-specified locations under set point changes despite the presence of load disturbance. The estimates of the polynomial $F(z^{-1})$ are: $\hat{f}_0 = 1$, $\hat{f}_1 = -0.639$ and $\hat{f}_2 = 0.00248$. The feed-forward feedback compensator gain is obtained to be ($H_d = 03195$). The parameters of the implicit PID pole placement controller (K_P, K_I and K_D), and the parameters of pole-placement compensator $q(z^{-1})$ are shown in table 2. Whereas, the parameters of the conventional PID controller are shown in table 3.

Table 2. The parameters of the implicit PID pole-placement control incorporating feed-forward feedback compensator.

v	K_p	K_I	K_D	$\hat{q}_0$	$\hat{q}_1$
2	1.2675	0.7275	0.005	0.4677	0.0706

Table 3. The parameters of the conventional PID controller.

K_p	K_I	K_D
-0.7438	0.7616	0.3778

4.2 Investigating the effect of the desired closed loop poles polynomial *T* on closed loop performance

This experiment was carried out in order to see the effect of the desired closed loop poles polynomial (T) on the closed loop system performance. The polynomial T was changed as follows:

$$\left.\begin{array}{ll} 0 \le t \le 200 & T_1 = 1 - .5z^{-1} \\ 200 \le t \le 400 & T_2 = 1 - 1.4z^{-1} + 0.49z^{-2} \\ 400 \le t \le 600 & T_3 = 1 - 1.6z^{-1} + 0.7z^{-2} \end{array}\right\} \quad (39)$$

The output and control input are respectively shown in Fig.(4a) and Fig.(4b).

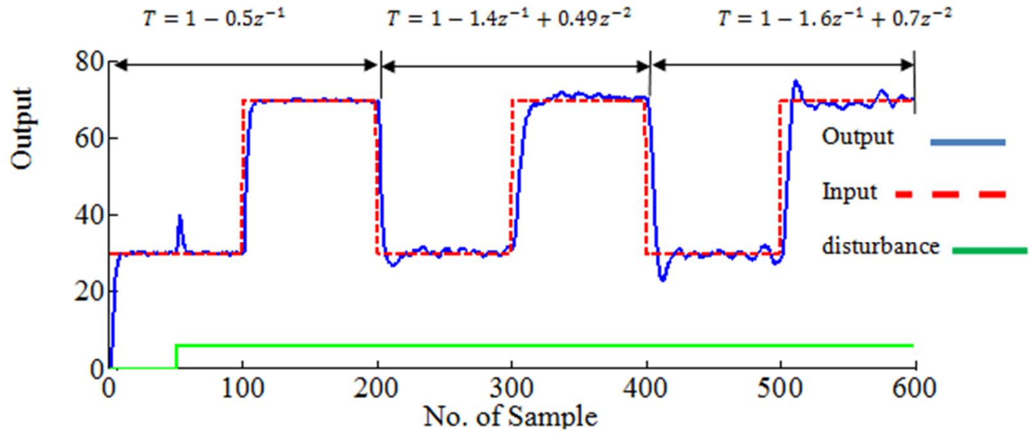

Fig.(4a): The output

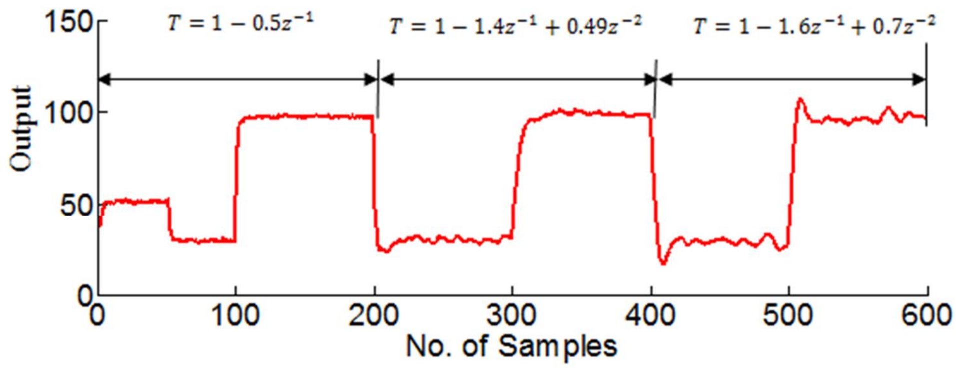

Fig.(4b): The control input

It can clearly be seen from both Fig.(4a) and Fig.(4b) that the performance of the closed loop changes by changing the polynomial T . It is obvious from these figures that at steady state, the proposed algorithm has the ability to regulate the measured disturbance to zero under the user-defined polynomial T changs.

5. Conclusions:

In this paper, a new computationally efficient algorithm to incorporate the robustness of Implicit PID pole-placement control and Feed Forward/Feedback control. The resulting Implicit PID Self-tuning Controller provides an adaptive mechanism which ensures that the closed loop poles is located at their pre-specified positions. It is effectively an implicit algorithm in the sense that the controller design step is trivial (solving Diophantine Eequation at each sampling instant is avoided). Furthermore, the results presented in section (4) indicate that the controller tracks set point changes with the desired speed of response. The transient response is shaped by the choice of the pole polynomial $T(z^{-1})$. A further research can be performed to extend this proposed design to a multiple controller which can be used as pole-placement, PID controller or PID pole-placement incorporating feed-forward feedback controller through flick a switch. The choice and selection of an appropriate control mode in practice, would involve determination of a trade-off between the various desired performance measures of the individual controllers (such as the minimum variance of controller outputs and inputs, relative computational complicity requirements, the desired transient response behavior including damping ratio, rise time, settling time, overshoot or bandwidth). In this case the switching between multiple controller modes can be adopted by using automatic switching mechanism. As in [15, 16] this may be achieved by using soft computing techniques or statistical methods such as simple logic, fuzzy logic, imprecise probabilities, stochastic learning automata.

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