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Performance Study of Combined Feedback and Feedforward Control

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Abstract : A moment ago many advanced control methods based on disturbance rejection have invented and proposed by researchers. These are transformed from understanding of automatic control, particularly the task of feedback and feedforward control. With this understanding, this work presents a feedback, feedforward and feedback plus feedforward control approaches for set point tracking method in general systems. In this, these acknowledged approaches are introduced and applied for higher order process model for better understanding of its design and implementation in simulation. The result obtained from these control schemes represent a close collaboration between feedforward and feedback controls. In realistic applications, feedforward control is normally used in combination with feedback control. Feedforward control is used to diminish the effects of measurable disturbances, while feedback control compensates unmeasured disturbances, inaccuracies in the process model and measurement error. A remarkable advantage of the combined feedback and feedforward approach is that control gives improved speed of response with accuracy. Finally, it is simulated to show the effectiveness of feedback, feedforward separately and combined.

Index Terms **- Feedback control, Feedforward control, Advanced control**

I. INTRODUCTION

The proper selection of any control scheme is depend on the process requirements and the characteristics of the controller [1]. Generally it can chosen depending upon the process dynamics, control objectives and cost. In process control most commonly used control scheme is feedback control due to its simplicity, accuracy and cost [2]. Feedback controllers measure and compare controlled variable to its desired value or set point and generate a correction signal by changing the controller output to a final control element. However, feedback control also has definite natural disadvantages like: it does not take corrective action until after a deviation in the controlled variable occurs. Accordingly, ideal control, where the controlled variable does not deviate from the set point during disturbance or set-point changes which is theoretically not possible. It does not offer predictive control action to compensate disturbance effect [3]. Due to this it may not be suitable for processes with large time constants and delays. In large time constant process, if regular disturbances arise then the process may operate continuously in a momentary state and never attain the desired steady state. Also it not feasible in some situations where the controlled variable measurement is not possible in on-line [1].

For overcoming some of these limitations, feedforward controller is considered. The fundamental idea of feedforward control is to measure important process disturbances and take corrective action before they disturb the process. It also has several disadvantages such as disturbances should be measured on-line which is not feasible in many applications. For effective use of this control, an approximate process model should be obtainable to know how the controlled variable counters to change in disturbance and manipulated variables [4]. Hence its quality is depends on the accuracy of the process model and ideally it is theoretically capable of achieving perfect control which may not be physically achievable [5]. As the model is an approximation and all disturbances are not measurable then feedforward control should always be used in combination with feedback control. Hence, this combination will compensate effect of measured and unmeasured disturbances as well as model mismatch [2]. For effective assessment of controller performance different approaches are investigated by researchers. In this work we assessed it by using error indices. Theoretical issues of control performance assessment are found in several literatures, such as the mentioned in [3-5]. Other developed techniques are found such as linear performance index based on minimum variance benchmark [6], a normalized performance index for assessment of linear SISO controller performance [7], performance assessment algorithm based on variance table to investigate the variance contributions due to disturbances and controllers for a linear feedforward and feedback system [7], approach based on filtering and correlation (FCOR) analysis of the process output and filtered data [8] and utilized autocorrelation and cross correlation functions for monitoring and diagnosing the cause of poor performance of feedforward and feedback control systems[9] .

In below sections, the detailed designs and implementation of feedback, feedforward and combined feedback plus feedforward controllers are explained. From obtained simulation results their comparative study made.

II. FEEDBACK CONTROL

In this section detail design of feedback control scheme is explained. Fig. 1 shows the block diagram of this control scheme. In this diagram $G_c(s)$, $G_p(s)$, $G_d(s)$, R(s), C(s), U(s) and D(s) represents controller, process, disturbance transfer function, reference input, controlled variable, controller output and input disturbance respectively. Feedback controller is accurate. It removes effect of all measured, unmeasured disturbances and set point change in controlled variable. But it is act after the effect of disturbances, hence it introduced lag in the overall system. Due to this such control scheme is not applicable for controlling of process with large time constants [10].

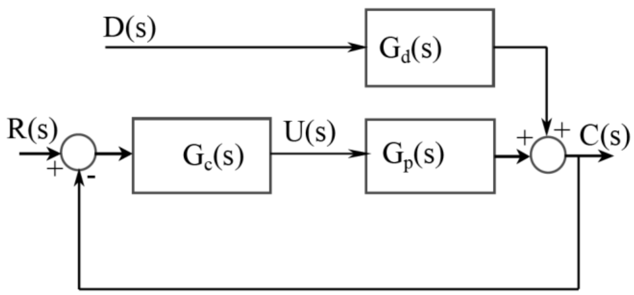

Fig. 1 Feedback control scheme

From above block diagram closed loop transfer function of the system is finding as:

$$G_{CL}(s) = \frac{G_p(s)G_c(s)}{1+G_p(s)G_c(s)} \qquad \text{Eq.(1)}$$

For stability condition roots of denominator polynomial of Eq.(1) must be lies in the LHS of the s-plane. For design of this controller higher order plus delay time process transfer function used. In this example for ease of design of controller the transfer function is approximated in to first order plus delay time (FOPDT) model [11] as given in below and PID controller's setting are found by using Ziegler-Nichols method mentioned in below table [10].

$$G_{FOPDT}(s) = \frac{k_p e^{-\theta s}}{\tau_p(s)+1} \qquad \text{Eq.(2)}$$

where k_p, τ_p and θ are steady state gain, time constant and delay time of process.

Table 1. PID parameters using Z-N method

Controller	K_c	T_i	T_D
PID	$\left(\frac{1.2}{K_p}\frac{\tau_p}{\theta}\right)$	2θ	0.5θ

After finding of PID controller parameters, feedback controller is successfully implemented for given higher order process model in simulation.

III. FEEDFORWARD CONTROL

As above mentioned, feedback control scheme is not applicable for controlling of process with large time constant. This limitation of feedback control is solved by using feedforward control system. This control scheme needs measurement of all disturbances. The feedforward control acts before the effect of disturbances in controlled variable, hence it is faster and applicable for controlling of process with large time constant. Fig.2 below shows block diagram of the scheme. In every process all disturbances are not possible, in this case it is not accurate and some time not able to control it. For example in heat exchanger control scaling and fouling are immeasurable disturbances. in this case combined feedback and feedforward control schemes are used [12].

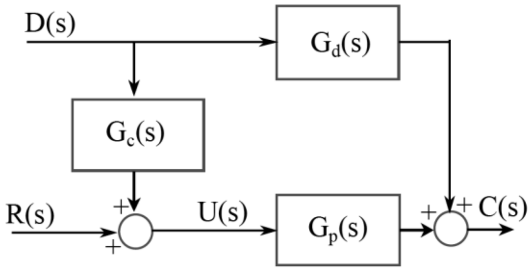

Fig. 2 Feedforward control scheme

Note that feedforward control design is only feasible if delay time in disturbance transfer function is greater than delay time in process transfer function ($\theta_d > \theta$) and it is designed as:

$$G_{ff}(s) = -\frac{G_d(s)}{G_p(s)} \qquad \text{Eq.(3)}$$

IV. Feedback Feedforward Control

As we discussed limitation of feedback controller for process with large time constant is overcome by feedforward controller. But it will lost the accuracy. Hence if we use combined feedback and feedforward control it includes both controllers advantages. Means this combination will give fast and accurate output results. In this control scheme feedforward controller take care of measured disturbances while feedback controller take care of unmeasured disturbances. Due to this it may be used in many process control applications in the industries [13].

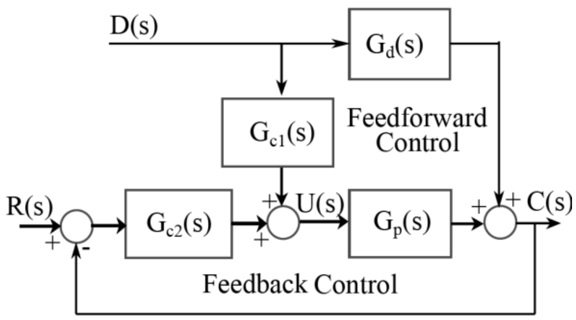

Fig.3 Feedback feedforward control scheme

In this control scheme $G_{c2}(s)$ is feedback controller and $G_{c1}(s)$ *is* forward controller. Thease two controllers are separately designed as above explained in above sections and finally both are combined as shown in Fig.3.

V. Example: Higher order process with delay

For better understanding of above controller, we are considered higher order process model with delay and simulated it in Matlab software. For design consider a process model as [11]:

$$G_p(s) = \frac{1-4s}{200s^3+150s^2+27s+1} e^{-0.1s} \quad \text{Eq.(4)}$$

5.1. Feedback control design

First find approximate FOPDT model of given higher order model for design of feedback control usign Tayler series expansion method. Obtained FOPDT model is [15]:

$$G_{FOPDT}(s) = \frac{1}{20s+1} e^{-11.1s} \quad \text{Eq.(5)}$$

Using Table-1, PID controller parameters are found from obtained FOPDT model as: K_c=2.16, T_i=22.2 and T_D=5.5. Designed PID controller is implemented for given process in Matlab Simulink as shown in Fig.4 and its obtained results are presented in Fig.7. In this example disturbance transfer function is taken as: $G_d(s) = \frac{0.25}{31s+1} e^{-25s}$.

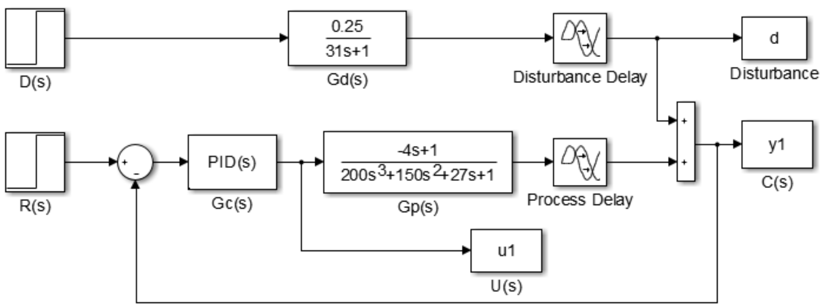

Fig.4 Feedback control simulation model

5.2. Feedforward control design

As discussed in feedforward control section, it is designed from approximate FOPDT process model and given disturbance transfer function as given in above Eq.(3). Designed controller is implemented as shown in Fig.5 and tested in simulation. Obtained results are presented in Fig.7 and compared with feedback control results.

$$G_{ff}(s) = \frac{-5s-0.25}{31s+1} e^{-13.9s} \quad \text{Eq.(6)}$$

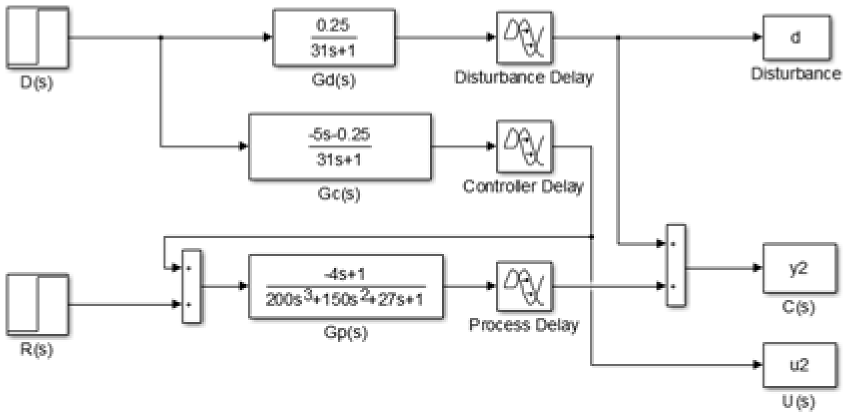

Fig.5 Feedforward control simulation model

5.3. Feedback-feedforward control design

In the most of industries accurate and fast control schemes are used for controlling of process. Such controllers are designed by combination of feedback and feedforward control schemes. In this example this combined controller is designed by combining of above designed feedback and feedforward controllers. The combined structure of the controller as shown in Fig.6 after simulations. Its obtained results are compared with feedback and feedforward controller's results which are presented in Fig.7.

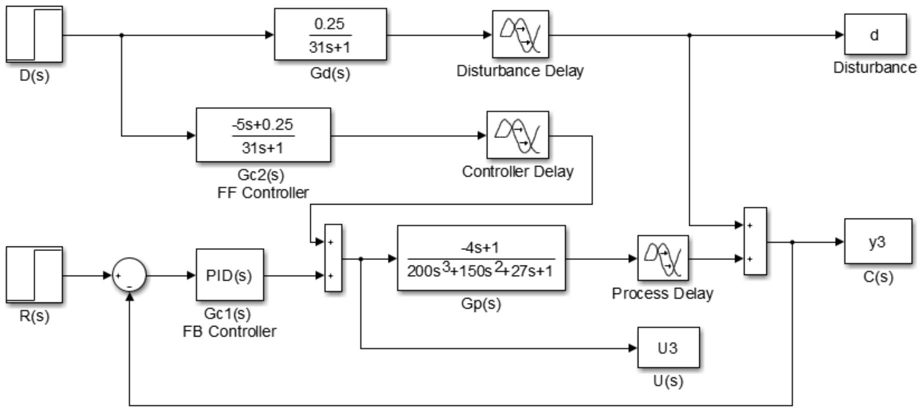

Fig.6 Feedback-feedforward control simulation model

VI. SIMULATION RESULTS

Using above discussed Simulink models, simulation closed loop responses for feedback, feedforward and combined feedback-feedforward control system are obtained, which are presented in the Fig.7. In this figure y1, y2 and y3 are the closed loop responses obtained for feedback, feedforward and feedback-feedforward controllers respectively. In this set point changed after 10 sec. time, disturbance d is applied at 250 sec. and 750 sec time. For better observation, effects of disturbance are zoomed. From zoomed results it is observe that feedforward controller compensate the effect of disturbance faster as compared to feedback controller. Feedback controller gives delayed but accurate result as compared to feedforward controller. Finally it also observed that combined feedback-feedforward controller gives faster and accurate results. For better understanding, closed loop performances of these controllers are measured by integral squared error (ISE), integral absolute error (IAE) and integral time weighted absolute error (ITAE). Measured error performance indices are given in tabulated form in Table-2.

Table 2. Closed loop performance measures

Controller	ISE	IAE	ITAE
Feedback	1999	309.8	0.6315
Feedforward	4167	626.0	0.0414
Feedback-Feedforward	1965	250.4	0.0330

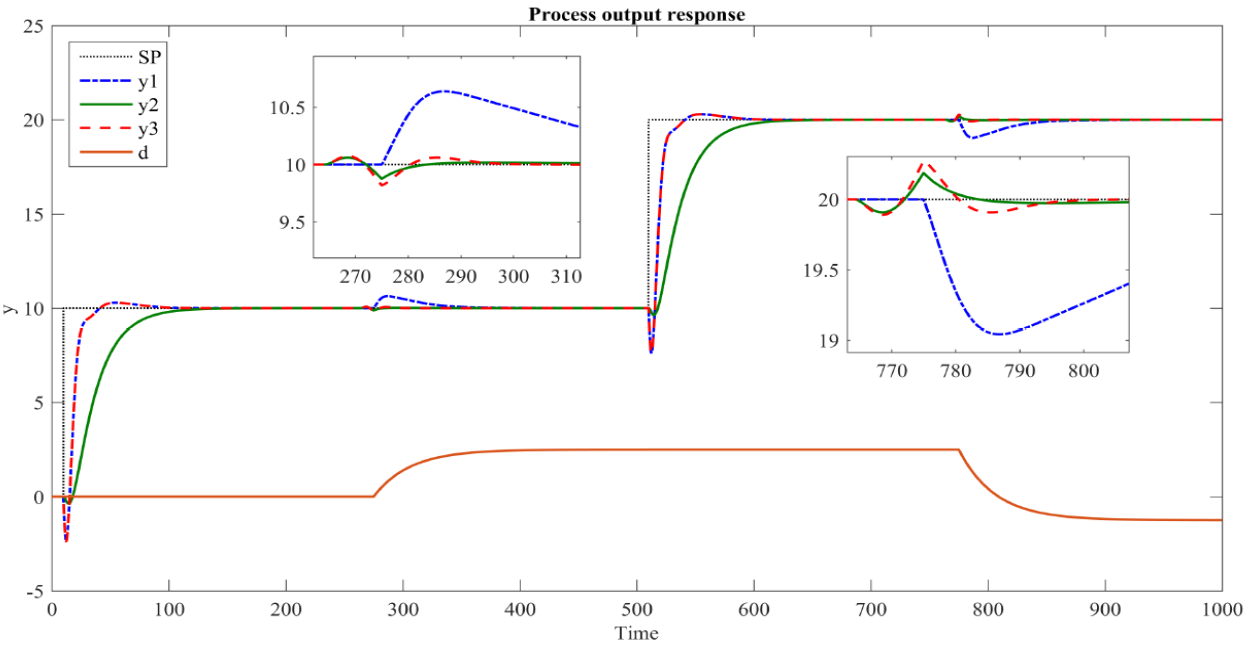

Fig.7 Closed loop response of feedback (y1), feedforward (y2) and feedback-feedforward (y3) control systems.

VII. CONCLUSIONS

In this paper, design of feedback, feedforward and combined feedback-feedforward controller are studied and successfully applied for higher order plus delay time process model. For better understanding these designed controllers are tested in simulation study. From obtained simulation results presented in Fig.7, it is observed that feedback controller gives accurate but delayed response, feedforward gives inaccurate with fast response and combined feedback-feedforward controller gives accurate and fast response. Also from error performance measures given in Table. 2, it also found that performance of combined feedback-feedforward controller is better than feedback and feedforward controller. Hence feedback-feedforward controller is the best choice of control scheme for controlling of any process.

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