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Set-point tracking of PI and PID controlled fast response flow system

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Abstract

The effectiveness of reference tracking of fast response flow system by conventional PI or PID controller depends on the process transfer function variables, and controller adjustable parameters. The first-order lag relationship of the flow process is obtained from the material balance, on assumption, that no reaction occurred between the input and output points. Process time constant and gain were varied from 0.005s-5s and 0.5-500 respectively while the system simple performance criteria were monitored. As expected, the controllers adjusted their time parameters by the same magnitude in which the process time constant increased, but showed insignificant change due to the increase in the process gain. The decrease in the controllers' response time from 0.005615s to 0.00107s resulted in increased speed for the system, but at the expense of stability. Based on that, a balance between response time and robustness is required to ensure optimum set-point reference tracking and desired system stability.

Keywords: *Reference, Fast Response, First-Order, Response Time, Process Gain.*

1. Introduction

Various response systems occur in the process control engineering. Flow control system is a fast response system that has wide applications in the regulating of process variables [1]. For example, the adjustment of the flow rate of one or more component can be used to control the temperature of a system. [2] maintained the outlet temperature of oil close to its set-point by regulating the oil flow rate. Flow control also has wide applicability in the level control of process systems with the objective of maintaining the level around the desired set point [3]. Therefore, it is essential for control engineers to understand the dynamics of the flow systems. In most flow systems, their responses to input change depend on their capacity. Multicapacity systems are slower in response due to their inherently higher damping coefficients. On the contrary, single capacity systems respond faster to input change, and therefore require appropriate control measures that will satisfactorily keep the output signal around the desired set point. Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers are used for this purpose. PI and PID controllers have been at the heart of control engineering practices for the last eight decades [4]. They have widespread acceptance in process control for variety of industries such as oil and gas, petrochemical, food and beverage, etc [5,6]. PID controllers are widely used in process industries because they are simple and easy to apply [7]. In order for the PI and PID controllers to effectively respond to the system, then the appropriate proportional, integral and derivative parameters must be selected. Therefore, proper tuning of the controller is a prime priority to the stability and performance of control systems [8]. By tuning the PID gain values, the characteristics of the closed-loop step response can be optimized to achieve a desired system output [9]. PID controllers also have additional functionalities (set-point weighting, anti-windup, etc) that allow the user to improve the performance in practical cases [10,11]. The composite proportional and integral action combined provides a balance of complexity and capability that makes it by far the most widely used algorithm in process control [12]. Specifically, they are used in flow systems [13] because they have the capacity to remove offset, and still operates within the acceptable speed. The integral component of the PI controller decreases the speed of the response but where the system response becomes sluggish; the derivative action is included to form a PID controller. The PID controller can provide the required speed and robustness through the stabilizing effect of the derivative component.

2. Methods

The model of the flow system given in the Figure 1 is obtained from the general material balance of Equation (1). The single capacity flow system is controlled by feedback mechanism. In a feedback control system, the output variables are measured and transmitted to the controller for appropriate control actions [14]. It is assumed that the rate of flow-in is higher than the rate of flow-out; therefore, there is accumulation in the tank which will ultimately attain a steady state.

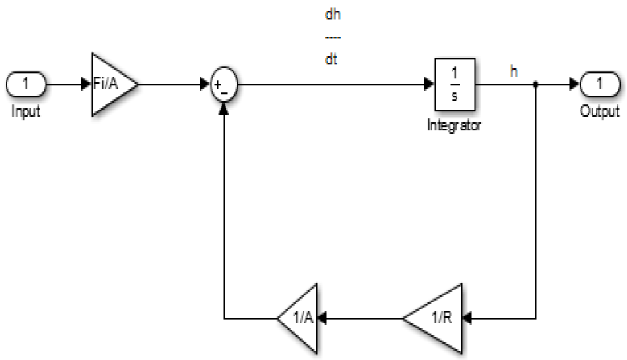

Figure 1: Flow system model

Applying the general material balance relationship gives:

Accumulation=Material in - Material out + Generation-Consumption (1)

It is assumed that there is no reaction or that all the chemical reactions have taken place prior to flow into the vessel, therefore, Generation=0 and Consumption=0. Equation (1) becomes,

Accumulation=Material in-Material out

$$A\frac{dh}{dt} = F_i - F \quad (2)$$

$$A\frac{dh}{dt} = F_i - \frac{h}{R} \quad (3)$$

Where $F = \frac{h}{R}$

Applying the deviation variables; h' and $F_i{}'$ in the equation above gives

$$AR\frac{dh'}{dt} + h' = Rf'(t) \quad (4)$$

Taking Laplace Transform of the equation

$$ARs[\bar{h}'(s) - \bar{h}(0)] + \bar{h}'(s) = R\bar{f}'(s)$$

(5) At initial conditions (t=0, h=0),

Therefore $ARs\bar{h}'(s) + \bar{h}'(s) = R\bar{f}(s)$ (6)

Substituting AR by τ_p (time constant) and R by k_p (steady –state gain),

Equation (6) becomes:

$$\tau_p s\bar{h}'(s) + \bar{h}'(s) = k_p\bar{f}'(s) \quad (7)$$

$$\bar{h}'(s)[\tau_p s + 1] = k_p\bar{f}'(s) \quad (8)$$

The transfer function is obtained:

$$G(s) = \frac{\bar{h}'(s)}{\bar{f}'(s)} = \frac{k_p}{\tau_p s+1} \quad (9)$$

Values of process time constant (τ_p) and steady-state process gain (k_p) in the range 0.005s-5s and 0.5-500 respectively were chosen, and the PI and PID controllers (Figure 2) dynamic responses were studied under the following conditions using MATLAB/Simulink software.

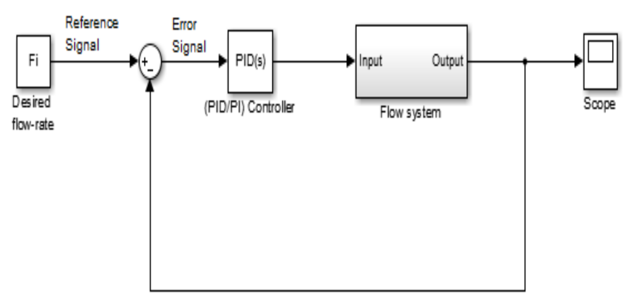

Figure 2: PI/PID controlled flow system

1. Increasing τ_p at constant k_p, controller response time and transient coefficient
2. Increasing k_p at constant τ_p and controller response time.
3. Increasing controller transient coefficient at constant k_p, τ_p and controller response time.
4. Increasing controller response time at constant k_p, τ_p and controller transient coefficient. The results are given in the tables 1 to 5.

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3. Results and discussion

Table 1 shows the reference tracking parameters obtained from the step plot of the feedback control of the process given in Equation (9). The process time constant (τ_p) is increased from 0.005 (at the multiples of 10) to 5 at constant steady state gain, response time and transient coefficient. Time constant is the length of time the system takes to reach approximately 63% of the steady state [15].

As τ_p increases from 0.005s to 0.5s, there is a corresponding change in the dynamic characteristics of the feedback control system. At τ_p=0.005s, the rise time of the PI controller is 0.00405s while the settling time is 0.0148. It is clear from the Table 1 that the rise time and settling time increase by the same geometrical ratio of 10 by which τ_p changes. The PI values of k_p, peak amplitude and overshoot% remain unchanged at 2.0848, 1.14 and 13.8 respectively. The only PI parameter that decreases as τ_p increases is controller integral gain (ki) which has the value 1251.36 at $\tau_p = 0.005$ but reduces to 1.2514 at $\tau_p = 5$.

Table 1: The step plot reference tracking parameters at constant k_p (k_p=0.5), controller response time and transient coefficient

Characteristics	PI	PI	PI	PI
τ_p	0.005	0.05	0.5	5
Response time	0.005615	0.05615	0.5615	5.615
Transient coefficent	0.6	0.6	0.6	0.6
Kp	2.0848	2.0848	2.0848	2.0848
Ki	1251.36	125.136	12.5137	1.2514
Td	-	-	-	-
Ti	0.001666	0.01666	0.1666	1.666
Rise Time	0.00405	0.0405	0.405	4.05
Settling Time	0.0148	0.148	1.48	14.8
Peak	1.14	1.14	1.14	1.14
Overshoot (%)	13.8	13.8	13.8	13.8

Characteristics	PID	PID	PID	PID
τ_p	0.005	0.05	0.5	5
Response time	0.005615	0.05615	0.5615	5.615
Transient coefficient	0.6	0.6	0.6	0.6
Kp	2.8631	2.8631	2.8631	2.8331
Ki	1037.92	103.792	10.3792	1.0379
Td	2.81E-07	2.81E-06	2.81E-05	2.81E-04
Ti	0.002758	0.027582	0.2758	2.7582
Rise Time	0.00456	0.0456	0.456	4.56
Settling Time	0.0158	0.158	1.58	15.8
Peak	1.06	1.06	1.06	1.06
overshoot (%)	6.1	6.1	6.08	6.08

PID controller exhibits similar dynamic characteristics in all the parameters. Furthermore, the controller has additional parameter, Td which increases from 2.8071E-07 to 2.8071E-04 as τ_p goes from 0.005 to 5. Comparing PI and PID controllers parameters, it is obvious that PID has less values of peak amplitude (peak=1.06) and overshoot (overshoot=6.1%). This means that PID controller achieves better stability because the less overshoot, the more stable a system is [16,17].

Table 2 shows the effect of varying k_p on the PI and PID controllers system. It is obvious from the Table 2 that at constant τ_p and constant controllers' response, and transient times, increase in k_p has insignificant effect on the control parameters.

Table 2: The step plot reference tracking parameters at constant process time constant (τ_p =0.005), controller response time, and transient coefficient

Characteristics	PI	PI	PI	PI
k_p	0.5	5	50	500
Response time	0.0056	0.0056	0.0056	0.0056
Transient coefficient	0.6	0.6	0.6	0.6
Kp	2.0848	0.2085	0.0208	0.0021
Ki	1251.36	125.136	12.5137	1.2514
Td	-	-	-	-
Ti	0.0017	0.0017	0.0017	0.0017
Rise Time	0.0041	0.0041	0.0041	0.0041
Settling Time	0.0148	0.0148	0.0148	0.0148
Peak	1.14	1.14	1.14	1.14
overshoot (%)	13.8	13.8	13.8	13.8

Characteristics	PID	PID	PID	PID
k_p	0.5	5	50	500
Response time	0.0056	0.0056	0.0056	0.0056
Transient coefficient	0.6	0.6	0.6	0.6
Kp	2.8631	0.2863	0.0286	0.0029
Ki	1037.92	103.792	10.3792	1.0379
Td	2.81E-07	2.81E-07	2.81E-07	2.81E-07
Ti	0.0028	0.0028	0.0028	0.0028
Rise Time	0.0046	0.0046	0.0046	0.0046
Settling Time	0.0158	0.0158	0.0158	0.0158
Peak	1.06	1.06	1.06	1.06
overshoot (%)	6.08	6.08	6.08	6.08

As k_p increases from 0.5 to 500, the PI peak amplitude and overshoot values of 1.14 and 13.8% respectively remain unchanged. This trend is also applicable to the PID peak amplitude and overshoot% which remain steady at 1.06 and 6.08% respectively. All the time parameters (rise time, settling time, Td and Ti) of both controllers are not affected by the increase in k_p. For both the PI and PID controllers, the controller proportional gain kp is the only parameter that decreases as k_p increases. The PI proportional gain is 0.20848 at k_p=5 but decreases to 0.0020848 at k_p=500. In the same way, PID controller shows a reduction of kp from 2.8631 to 0.0029 as k_p is adjusted from 5 to 500.

Table 3 shows the effect of increase in controller transient coefficient (robustness) on the PI and PID controllers at constant k_p , τ_p and controller response time. Robustness is the ability of the system to remain functioning under a wide range of disturbances [18].

Table 3: The step plot reference tracking parameters at constant k_p,τ_p, and controller response time.

Characteristics	PI	PI	PI	PI
Transient coefficient	0.6	0.66	0.73	0.8
Kp	0.2085	0.2441	0.2822	0.3161
Ki	125.136	116.6886	105.2241	92.1909
Td	-	-	-	-
Ti	0.0017	0.0021	0.0027	0.0034
Rise Time	0.0041	0.0042	0.0045	0.005
Settling Time	0.0148	0.0153	0.0158	0.0151
Peak	1.14	1.1	1.06	1.03
Overshoot (%)	13.8	10.2	6.49	3.19

Characteristics	PID	PID	PID	PID
Transient Coefficient	0.6	0.66	0.73	0.8
Kp	0.2863	0.2701	0.2822	0.3161
Ki	103.792	109.1556	105.2241	92.1909
Td	2.81E-07	2.81E-07	2.81E-07	2.81E-07
Ti	0.0028	0.0025	0.0027	0.0034
Rise Time	0.0046	0.0044	0.0045	0.005
Settling Time	0.0158	0.0153	0.0158	0.0151
Peak	1.06	1.08	1.06	1.03
overshoot (%)	5	5	5	5

As the robustness of the controllers increase, the time parameters (rise time, settling time and Ti) also increase as well. The rise times of the PI controller are 0.00405s, 0.00423s and 0.00452s at 0.6, 0.66, and 0.73 set robustness respectively. On the other hand, the PID rise time parameter indicates an oscillation as transient coefficient increases from 0.6 to 0.66. The value of the rise time, first decreases from 0.00456 to 0.00441, then increases to 0.00496 at 0.8 transient coefficient.

Table 4 shows the effect of controller response time adjustment on the feedback control systems. At constant k_p , τ_p and controller robustness, decrease in controller response time results in decrease of time parameters of the PI and PID control systems. The rise time and settling time parameters of the PI controller at 0.0056s (controller response time) are 0.00405s and 0.0148s respectively. These values decrease to 0.000699s and 0.00457s respectively at 0.00107s controller response time.

Table 4: The step plot reference tracking parameters at constant k_p, τ_p, and controller transient coefficient

Characteristics	PI	PI	PI	PI
Response time	0.005615	0.003383	0.001859	0.00107
Transient Coefficient	0.6	0.6	0.6	0.6
Kp	0.2085	0.412	0.8316	1.5189
Ki	125.136	277.1194	764.9022	2071.0779
Td	-	-	-	-
Ti	0.0017	0.0015	0.0011	0.0007
Rise Time	0.0041	0.0024	0.0013	0.0007
Settling Time	0.0148	0.0096	0.0056	0.0046
Peak	1.14	1.16	1.19	1.21
overshoot(%)	13.8	16.5	19.2	21.1

Characteristics	PID	PID	PID	PID
Response time	0.005615	0.003383	0.001859	0.00107
Transient coefficient	0.6	0.6	0.6	0.6
Kp	0.2863	0.514	1.0132	1.7908
Ki	103.792	209.232	444.171	1069.777
Td	2.81E-07	1.69E-07	9.30E-08	5.35E-08
Ti	0.0028	0.0025	0.0023	0.0017
Rise Time	0.0046	0.0027	0.0015	0.0009
Settling Time	0.0158	0.011	0.0074	0.0049
Peak	1.06	1.08	1.08	1.09
Overshoot (%)	6.08	8.09	7.78	9.24

Similarly, the PID control system parameters (rise time and settling time) exhibit the same characteristics when the response time is adjusted from 0.0056s to 0.00107s. While the time parameters of both control systems decrease with the response time, the peak amplitude and overshoot% fairly increase. The peak amplitude and overshoot of the PI controller are 1.14 and 13.8% at 0.0056s controller response time. As the controller response time decreases to 0.00107s, the peak amplitude and overshoot increase to 1.21 and 21.1% respectively.

4. Conclusion

The set-point tracking of PI and PID-controlled fast flow system has been simulated with MATLAB software at monitored process parameters and controllers' dynamic characteristics. Smaller values of τ_p used in the simulation ensured that the system was operated in a condition similar to a real and practical fast response system. The transient coefficient is shown to be the most significant controller dynamic characteristics, as it affected the system stability when adjusted rightward. Therefore, a trade-off between robustness and response time is required to ensure the achievement of optimum reference tracking, and at the same maintains desired system stability.

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