PID TUNING WITH INPUT CONSTRAINT: APPLICATION ON FOOD PROCESSING

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ABSTRACT

PID controllers are probably the most common used industrial controller. PID controller has gone through few decades and has survived successfully through the changes of technology from analogue era into digital era. Actuator saturation is among the most common and significant problem in control systems design as it may lead to instability and consequently affect the performance of the process. Normal PID controller does not take this into consideration. Normally, an anti windup compensator is added as the remedy for this constraint. For alternative, this research investigates the possibility to tune PI controller when the system is under saturation. This research will put emphasis on first order plus time delay process and an expression is developed for saturation level, U as a function of controller gain, c K with the range of R 0.8-2 (ratio of time delay to time constant). Simple and accurate correlations are obtained for the saturation level (u) and controller gain, K_c.

The proposed relations overcome this input constraint by explicitly considering the saturation level during the tuning of PI controller. Thus, saturation can be avoided and at the same time, it gives satisfactory performance. This method is named as BL tuning method and applied on spray drying process. The results showed that this BL tuning method could give satisfactory performance in controlling the process.

Keywords: *PID controller, tuning of PID, input saturation.*

INTRODUCTION

PID controllers are probably the most common used industrial controller. It was the first controller to be produced intensively to fulfil the great demand for controller at existed process plants. The PID controller calculation involves three separate parameters which are Proportional, Integral and Derivative values. The Proportional value determines the reaction to the current error whereas the Integral determines the reaction based on the sum of recent errors and finally Derivative determines the reaction to the rate at which the error has been changing [1]. Tuning of a PID involves the adjustment of K_p, K_i, and K_d to achieve some optimal character of system response [2,3,4]. If the PID controller parameters (the gains of the proportional, integral and derivative terms) are chosen inappropriately, the controlled process input can be unstable, for instance, its output diverges, with or without oscillation [4]. Ziegler-Nicholas methods and their extensions of related rules had become the foundation and given ideas for the engineers to design the rules and empirical formulae for PID controller [5]. However the ZN method did not applicable to all industrial process. This had lead to intensive research on other alternatives to improve the PID tuning procedure.

There are several recommendations for tuning PID controller parameters, for examples Direct Synthesis (DS), Abbas method (AA) and Cohen-Coon [6,7,8]. However, the current PID controller is unable to handle this input constraint. Actuator saturation is one of the hard nonlinearity in control problems. There have been little efforts emphasized on actuator saturation and it was often been ignored or given a minor treatment in most of the modern control literature. When the actuator saturates, the performance of the closed-loop system designed without considering actuator saturation may lead to instability of the plant. In extreme cases, the system stability may even be lost [9]. Normally, an anti windup compensator is added as the remedy for this constraint but this research will investigate the possibility to tune PI controller when the system is under saturation. Performances between of BL tuning method and several existing tuning methods were compared.

MATERIALS AND METHODS

The closed-loop transfer function, *T(s)*, is given by equation 1 and only first order plus time delay (FOPTD) is considered.

$$T(s) = \frac{Y(s)}{X(s)} = \frac{Gc(s)G_p(s)}{1+Gc(s)G_p(s)} \qquad (1)$$

$$G_p(s) = \frac{Kp\ e^{-\theta s}}{\tau ps+1} \qquad (2)$$

Analogous to the method used in the IMC controller synthesis method, $c\ K$ and TI are obtained as below:

$$K_c = \left(\frac{\tau+\frac{\theta}{2}}{K_p(\lambda+\theta)}\right) \qquad (3)$$

$$T_I = \tau + \frac{\theta}{2} \qquad (4)$$

Only Integral time, T_I derived from IMC method is used in BL tuning method. Intensive simulations were done to find the relationship between saturation level and Proportional gain of controller, K_c. In what follows, an expression was developed for the saturation level, u as a function of K_c by utilizing MATLAB control toolbox. The range of ratio of time delay to time constant, R was within 0.8 and 2. Two time constant and two process gain were considered which were τ =1 and 2 and K_p =1 and 2 respectively. The relationship between saturation level and the controller gain is in Equation 5.

$$U = AK_c + B \qquad (5)$$

For each R, equation which produced smallest K_c will be chosen. It was because when a controller with input constraint, U and was substituted in Equation (5), it would give smaller K_c. This K_c was applied to the model run by SIMULINK and it would subsequently reduced the maximum control signal. If the maximum control signal was lower than the input constraints implemented to the system, it would thus prevent saturation.

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Table 1: Parameter A and B of BL tuning method.

Parameters	A	B
0.8	1.2929	0.2773
0.9	1.155	0.3603
1	1.6719	0.0416
1.1	1.5157	0.115
1.2	1.0983	0.4836
1.3	1.2324	0.4034
1.4	1.3071	0.398
1.5	1.555	0.2463
1.6	1.7371	0.1471
1.7	1.8236	0.1182
1.8	1.6836	0.1479
1.9	1.4419	0.3304
2	1.5038	0.3282
0.8	1.2929	0.2773
Average	1.463 ± 0.231859	0.261 ± 0.136589

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Parameters A and B of BL tuning method was shown in Table 1.After obtaining all values of A and B for each R, average of A and B was taken to obtain relationship of saturation level, *u* as a function of controller gain, K_c . Finally, equation was obtained as below and it was named as BL tuning method.

$$U = 1.463\, K_c + 0.261 \qquad (6)$$

SIMULATION STUDIES

In my study, spray drying model was developed by using experimental method. The empirical model was obtained by process reaction curve by determining the magnitude of input changes (δ) and the magnitude of process output changes (Δ). The process gain, K_p can be determined by dividing the magnitude of output changes to the magnitude of input changes. When the process output is reached at 63.2%, the time is time constant of process (τ). From the experiment data, Δ = 20; δ = 10; θ = 0.3 min and from the process reaction curve, the τ = 7.8 min and K_p =2. These parameters were substituted into the Equation 2 and it will become:

$$G_p\,(s) = \frac{2e^{-0.3s}}{7.8s+1} \qquad (7)$$

Performance of the spray drying process with PI controller that tuned by BL tuning method, Ziegler-Nicholas (ZN), Direct Synthesis (DS) and Cohen-Coon tuning methods were then be compared. The simulation was done in SIMULINK from MATLAB with simulation time of 200 s. In the simulation, first order plus time delay dynamic model (FOPDT) and PI controllers were employed. In this section, the performances of the spray drying process with and without saturation between existing tuning methods and BL tuning method were compared. Comparing results based on a single criterion can be misleading. The nature of the response should also be taken into consideration. Therefore, in this study, IAE values, percentage of overshoot, settling time of the process tuned by ZN, CC and DS were compared with BL tuning method.

RESULTS AND DISCUSSIONS

Performance Comparisons

In order to have input saturation, the maximum control signal was identified in Figure 1. The lowest control signal was about *U*=1. Thus, -0.7<*U*<0.7 which was lower than the maximum control signal of all tuning methods was chosen in order to cause saturation of the system. The system with existing tuning methods was saturated except for the system with PI tuned by BL tuning method and it was proved in Figure 2.

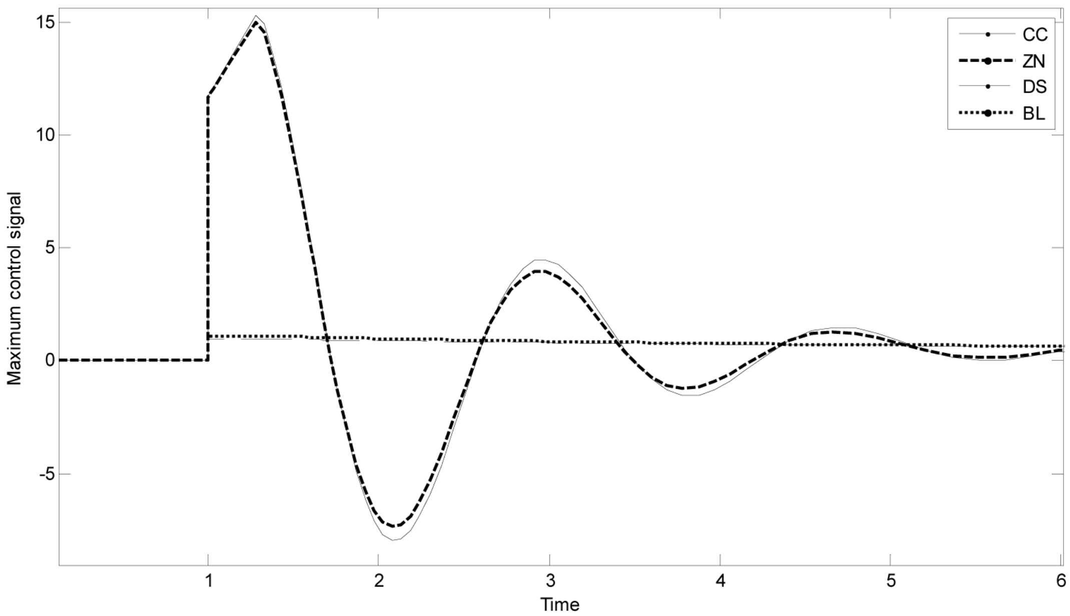

Figure 1: Maximum control signal for different tuning methods

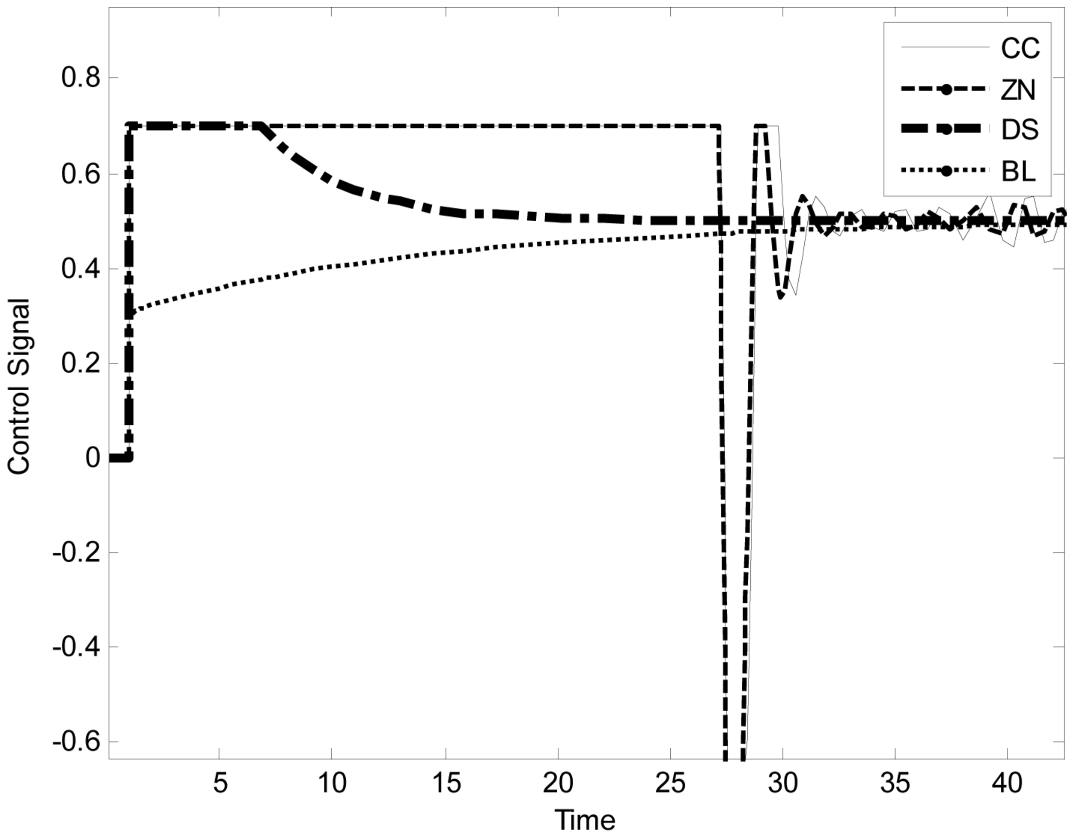

Figure 2: Control signal for different tuning methods under saturation (-0.7<U<0.7)

The output response with and without saturation were presented in Figure 3 and Figure 4. At a glance, except for process with PI tuned by BL tuning method, the rest obtained high percentage of overshoot and the output response was also too oscillatory. It was shown that the output response of the process with PI tuned by BL tuning methods was smooth and without any percentage of overshoot with and without input saturation. The weakness of the process with PI tuned by BL tuning method had larger rise time which would result in sluggish response.

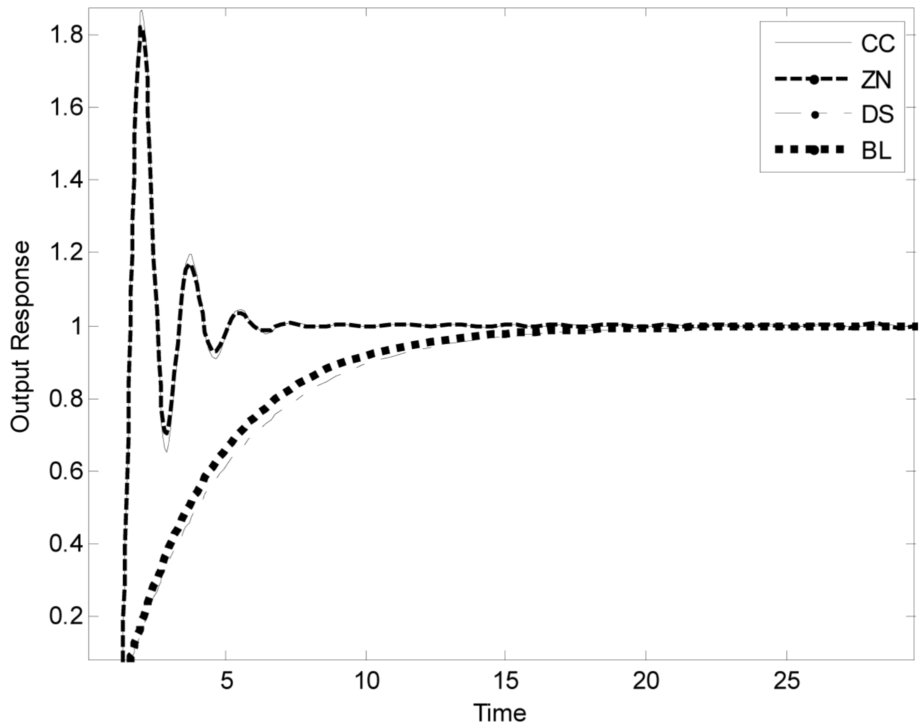

Figure 3: Output response for different tuning methods without saturation.

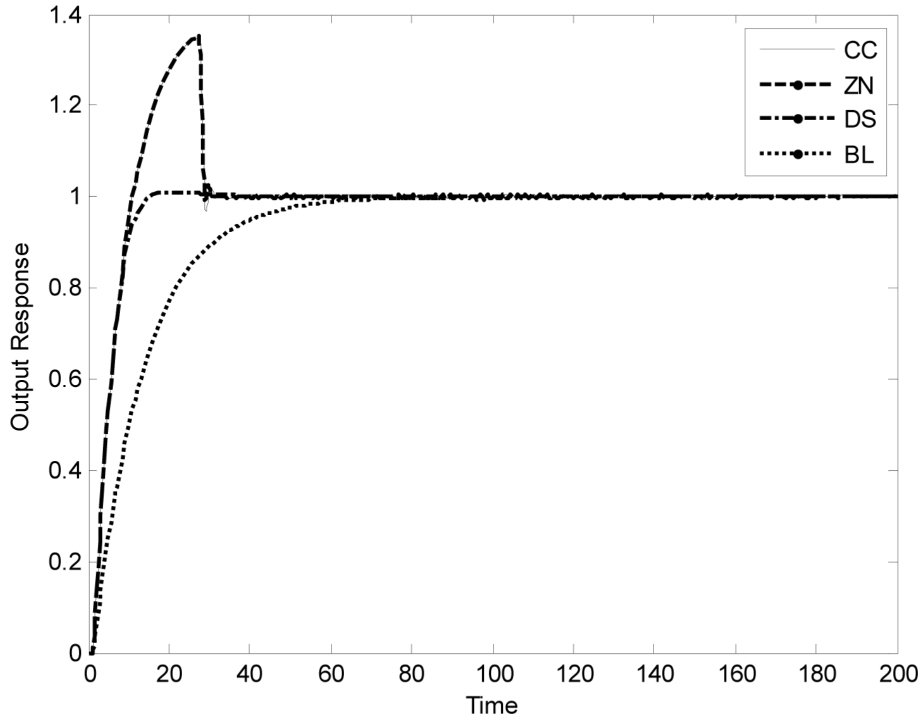

Figure 4: Output response for different tuning methods with saturation

Few saturation limits were set which were -1.3<*U*<1.3, -1.1<*U*<1.1 and -0.7<*U*<0.7. When these saturation limits were implemented to PI controller and it would cause input saturation as shown in Figure 2.These input constraints was also applied to the PI controller tuned by BL tuning method in order to show that the process tuned by new proposed BL method would not cause the controller to saturate although the tighter input constraint was imposed. It was clearly shown in Figure 5.

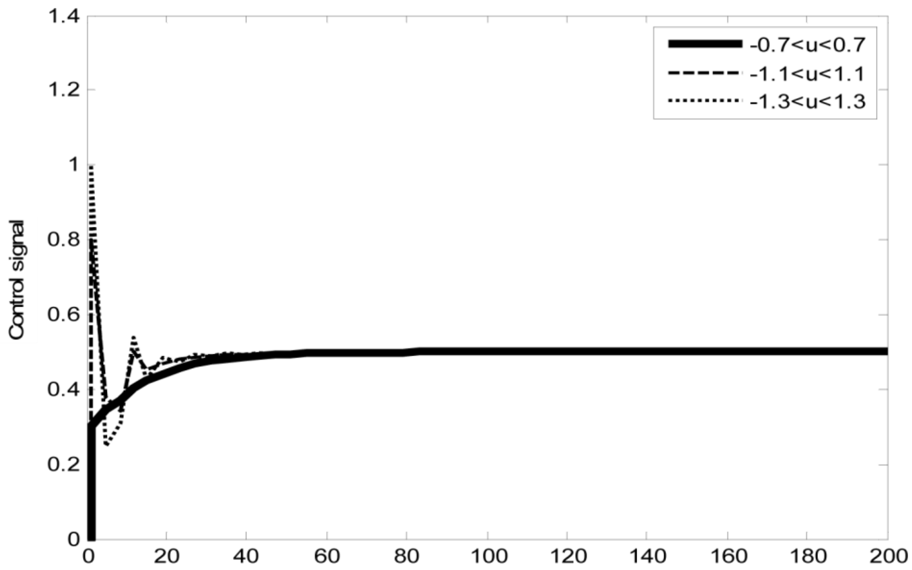

Figure 5: Control signal of BL tuning methods for different input constraints

The process with PI controller tuned using the CC tuning method showed the worst performance in terms of IAE criterion as it gave the highest value for IAE whereas the process tuned by BL tuning method showed the best performance in terms of IAE criterion as it gave the lowest value for IAE when without the presence the saturation. When there was saturation, performance in terms of the IAE values of the process tuned by BL tuning method was slightly poor than CC and ZN tuning methods. It was because of the fact that when there was an input saturation, integrator continued to integrate the error.

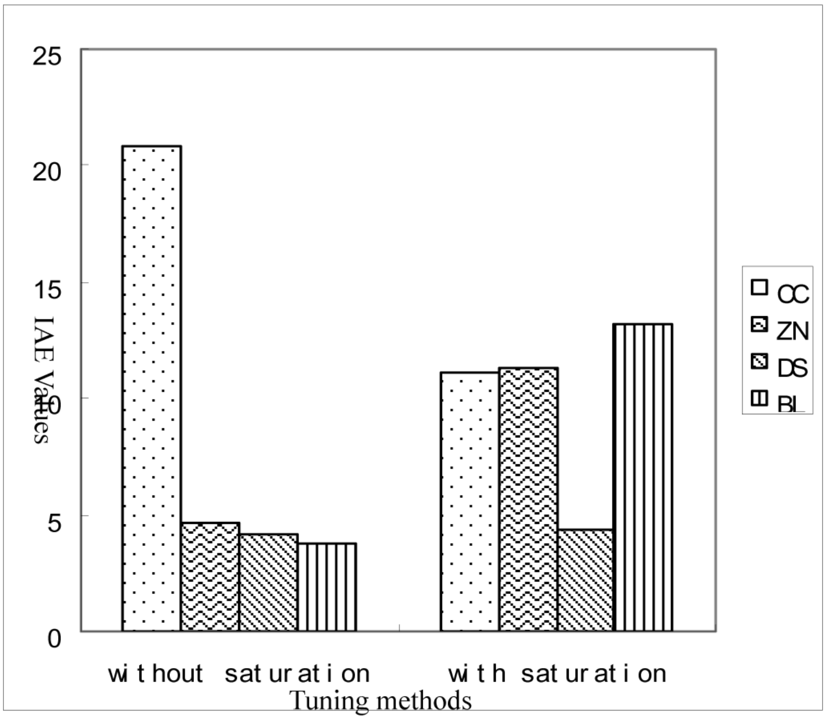

Figure 6: IAE values for different tuning methods

The process with or without actuator saturation which tuned by BL tuning method obtained zero percentage of overshoot indicated the system less oscillatory than CC, DS and ZN. Although the system tuned by CC, DS and ZN generated low IAE values, but their response indicated intolerably high overshoots. This was due to the fact that when the actuator is saturated, the integral term in PI controller would keep integrating the error, causing windup which resulted in large overshoot, and this may lead to instability of a system.

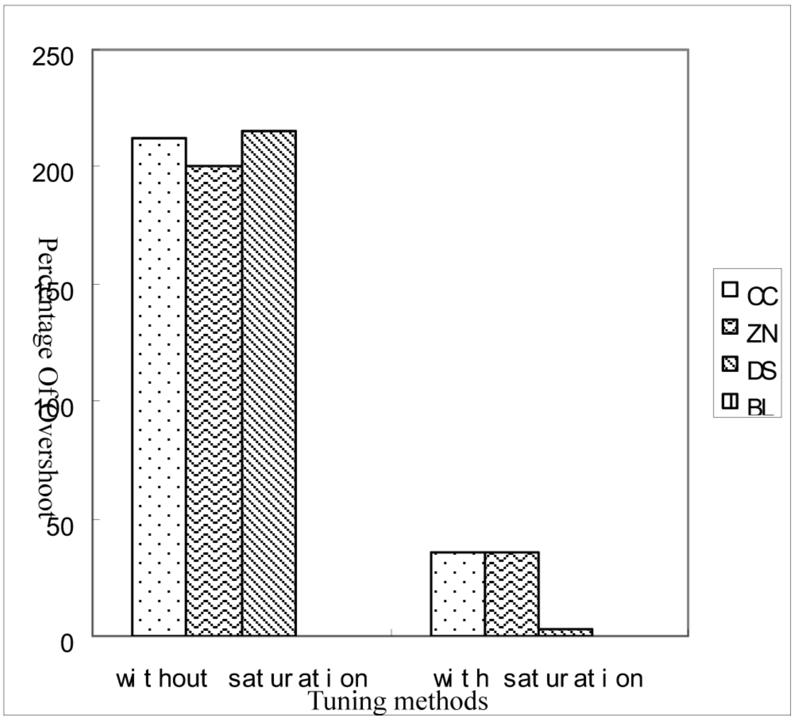

Figure 8: Settling time of different tuning methods

CONCLUSIONS

BL tuning rule is simpler and lesser parameter needed in tuning. The controller tuned with BL tuning method obtained better performance in terms of IAE criterion, zero percentage of overshoot and shortest settling time compared to Ziegler-Nichols, Cohen-Coon and Direct Synthesis tuning methods when it is not saturated. While with the presence of input saturation, performance of IAE is slightly higher but it still obtains zero percentage of overshoot and lowest settling time. BL tuning method was applied to PI controller in spray drying process. The results showed that this controller with BL tuning method could give satisfactory performance in controlling the process. As a conclusion, PI controller tuned by BL tuning method can perform well with or without the presence of saturation.

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