# Design of an Adaptive Self-Tuning Smith Predictor for a Time Varying Water Treatment Process

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**Abstract:** This paper presents the simulation and real time implementation of an adaptive predictive PI controller for the control of Chlorine dosing in secondary water disinfection rigs. This trial is part of a project that looks at the optimisation of process control specifically in the water industry. As one of the main treatment processes, Chlorine dosing is one of the processes that naturally imposes very long dead times for the controller to deal with. Although PI controllers are still commonly used for controlling this process, previous literature as well as trials carried as part of this project proved that the performance of PI controllers, no matter how tuned they are, is very sluggish and unreliable. A pilot rig was used instead of a live secondary disinfection rig, and a number of open loop step tests were performed for system identification. Once the process dynamics became known, complementary functions that estimate the process transfer function based on the water flow were introduced. A standard tuned PI controller configuration was simulated for the process, and then a Smith predictor was used in order to be able to compare the performance of the predictive PI with a standard PI controller. Tuning functions were derived for the PI to make it a self-tuning predictive controller, and parameter estimation functions were also used so that the final outcome is an adaptive self-tuning system. This system was then implemented on the same pilot rig, and real time implementation proved the findings obtained from the simulation. Both simulation and pilot rig tests show a very good dynamic response with excellent accuracy.

*Keywords*: Water process control; Chlorine dosing; PI tuning; Smith predictor; adaptive self-tuning.

## 1. INTRODUCTION

Process dead time is one of the most challenging issues in process control system design, as it makes the process difficult to control using standard feedback techniques mainly because the control action takes some time affect the controlled variable, and therefore the control action that is applied based on the actual error tries to correct a situation that originated some time before [1]. There can be several causes of this time delay, but in most process industries, the delay is caused by mass or energy transportation (also known as transport delay).

Processes with long dead times can not often be controlled effectively using a simple PI/PID controller. This is because the additional phase lag caused by the time delay tends to destabilise the closed loop system. The stability of such system can be improved by decreasing the controller gain, but that will certainly slow the controller down and make the response very sluggish [2]. Most water treatment processes incur relatively long transport delays, simply because the process variable is controlled by the addition of certain chemicals where a reaction time (Time taken for the chemical to dissolve/react in water) is to be allowed before the process variable can be sampled. It therefore, becomes part of the design requirements to allow enough distance between the chemical dosing and sampling points, and the time delay is then a function of the water flow within this distance as well as the flow in the sample line. A valid estimation of the delay may be expressed as:

$$Td = V/Q \tag{1}$$

Where Td is time delay, V is the volume of the pipe work between the dosing and sampling points, and Q is the water flow rate through the pipe. Another element that may have to be considered is the delay that might be caused by the sample line unless this delay is much smaller than the time delay caused by the pipe work. Previous research showed that PI controllers have been used to control dead-time processes, and the performance was acceptable when the dead time was small, but the performance deteriorates as the dead time increases, and in such cases a significant amount of detuning is required to maintain closed loop stability [5, 6].

## 2. THE CHLORINATION PROCESS

This research project focused on the implementation of predictive control for time varying water treatment processes that can generally be represented by a first order plus dead time (FOPDT) transfer function. Chlorine dosing is one of the essential treatment processes in most treatment plants as Chlorine is the most commonly used disinfectant and has been for the last hundred years [4]. The disinfection process takes place mainly in the main treatment plant, but there are usually secondary disinfection points spread around the distribution network in order to ensure that water provided to customers is microbiologically safe. Chlorine has many advantages that make it a more desirable disinfectant to use than other disinfectants (e.g. Ozone), but there are also disadvantages on using Chlorine. One of the main concerns in using Chlorine as a disinfectant is the formation of disinfection by products (DBP). Chlorine reacts with natural organic matter in water to form DBP's, and researchers are becoming increasingly concerned about the health problems those products can cause. A trade-off between the protection from infectious diseases and limiting exposure to DBP's has to be considered when using chlorine as a disinfectant [4]. This highlights the sensitivity of the Chlorination process, and the importance of having a reliable accurate control system to ensure that the amounts of Chlorine dosed in drinking water is what is needed.

## 3. PARAMETER ESTIMATION

The process described here is implemented on a pilot rig to study the effects of time varying processes on the performance of the controller. The advantage of using this pilot rig is the flexibility it gives in terms of controlling the parameters defining the dynamics of the process (i.e. water flow, pressure, and incoming Chlorine residual). These parameters have a direct impact on the process transfer function, and are normally hard to control in live disinfection rigs as they depend on water consumption by consumers.

Open loop step tests were performed at various flow rates and repeated several times. As expected, the variation of flow affected the dead time and the process time constant. Theoretically the dead time can be calculated using equation (1) provided that the precise volume of the pipe work as well as the precise flow rate are both known. Because of the relatively small size of the rig where even small inaccuracies in either the flow or the volume would affect the estimated process parameters, it was necessary to estimate the dead time using the open loop step test results. Figure 1 shows the relationship between the water flow rate and the process parameters.

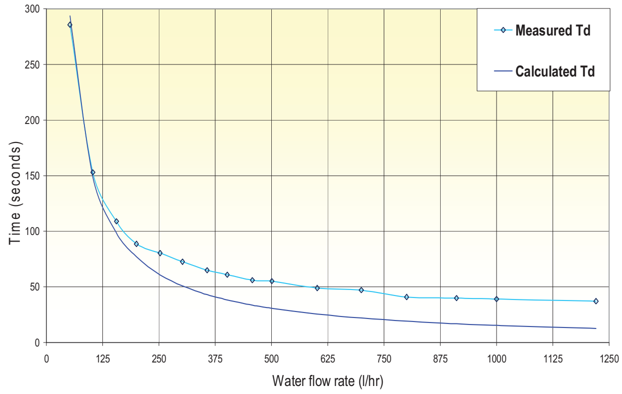


Fig. 1. Calculation and measurement of process dead time in relation to water flow rate.

It can be clearly noticed that at low flow rates, the measured dead time is almost identical to the calculated values, but as the flow increases beyond the lower 10% of this trial's flow range, the decrease in process dead time is not as expected. This highlights the importance of using real time data analysis when optimising the control system in this application.

## 4. PROCESS SIMULATION

Based on the open loop step test results, a model was built to represent both the process and the PI controller as implemented in most water treatment processes. Most chemical dosing process in water treatment use feedback plus feed forward control in a layout known in industry as Flow paced plus trim (Compound) control. The idea here is to combine the outputs of the feedback controller (usually a standard PI controller) and the feed forward controller (a gain element that is proportional to the water flow rate) in what will become the manipulated variable. In an ideal case, the feed forward controller output should keep the process variable equal to or very close to the set point. However, due to offsets in the dosing and measurement equipment, mismatch between the nominal and actual Chlorine strength, as well as the usual possibility of Chlorine presence in the incoming water, the feed forward controller will have to be supported by a feedback controller to act as a final trim and make up for all existing offsets.

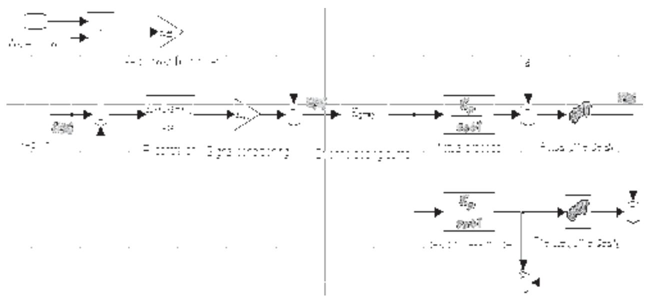

Fig. 2. Layout of Chlorine Dosing control loop.

A Smith predictor layout is shown in figure 2 combined with the PI controller and a proportional flow pacing function for feed forward control. The two main disturbances that can affect the process are the variation of water flow over time, and the incoming residual to the process. Many secondary disinfection rigs are installed on varying flow lines, where the flow rate changes over time by a ratio of up to 1:8. Therefore, it's important to consider the effect such big changes will have on the transfer function of the process, especially on the dead time of the process. Figure 3 shows a plot of real time data collected over a week from a time varying secondary dosing rig that is controlled by a PI controller.

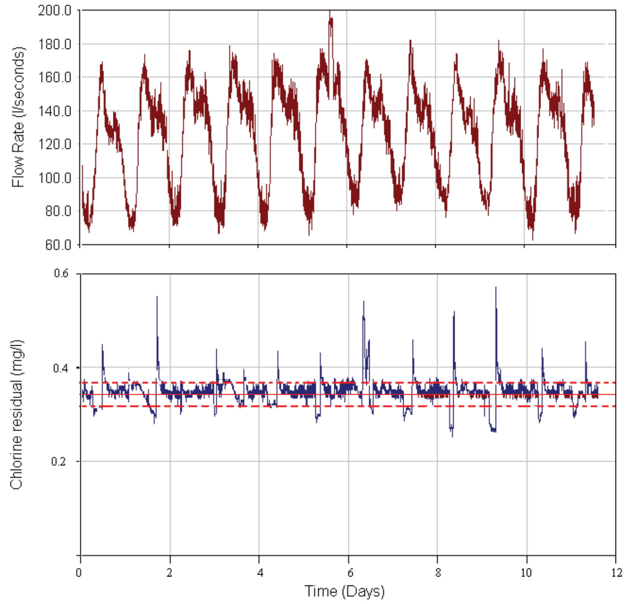


Fig. 3. Effect of time varying flow on the process variable (Chlorine residual).

The plot in figure 3 shows a clear link between changes in the water flow rate and variation in the Chlorine residual. Ideally, the Chlorine residual is supposed to remain within the band defined by the dashed lines for 99 % of the time for the system performance to be considered acceptable. Open loop step tests proved that the process time constant is also affected considerably by significant changes in the water flow rate. It is, therefore, obvious that in real applications, the practical approach would be to design a controller that will compensate for the inherent long dead times, and that will also be robust enough to the two major disturbances (i.e. Water flow rate changes, and incoming residual). For processes that are not time varying or where the variation is not that significant, PI controllers could produce what can be considered an acceptable performance. The more realistic scenario is the process where either one or sometimes all disturbances are significant, and that was the focus of this trial. The model in figure 2 was simulated. The process gain, time constant and dead time were all replaced with functions of the water flow rate that would make this an adaptive predictive controller. All the other gains are representative of the actual dosing and flow pacing constants. Figure 4 shows the closed loop step response of the simulated Smith predictor.

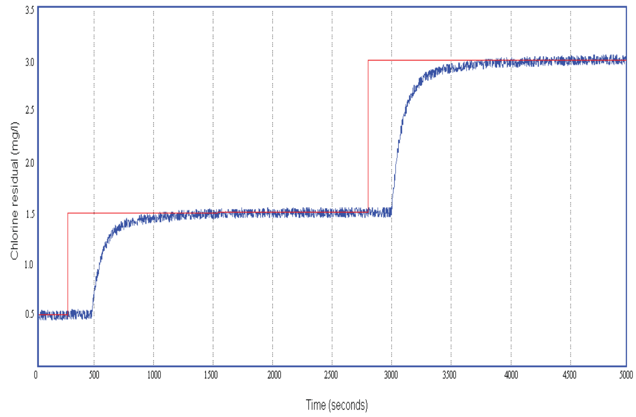


Fig. 4. Closed loop response of a simulated Smith predictor.

As mentioned earlier, the process parameters are flow dependent. A relatively low flow rate of 100 l/hr was chosen here to be able to simulate a challenging operational condition compared to a fast process. The above response shows that the controller performs well at set point tracking, and that accuracy and stability are maintained. The speed of response of the controller to the step changes is also very good considering the fact the dead time in this particular case was around 3 minutes. The same process model was simulated in closed loop using a standard PI controller that was also tuned using the same method that was used to tune the Smith predictor. It was noticed that at low flow rates, the dynamic response exhibits large un-damped oscillations as shown in figure 5.

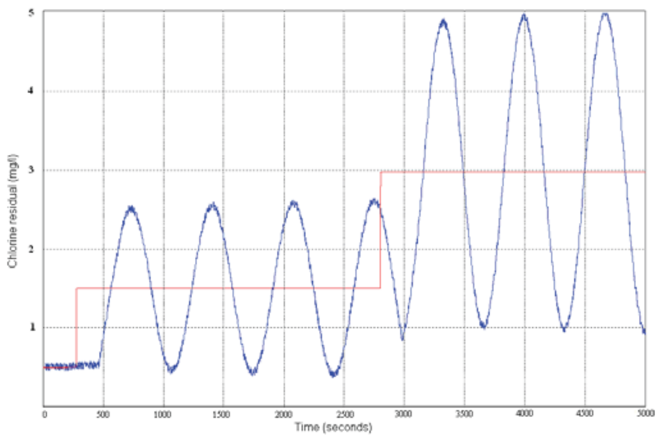


Fig. 5. Performance of a standard PI controller for a relatively long dead time process.

PI controllers are still being widely used in such processes. The only explanation as to why they are still being used is that in most cases the controller gain will be kept at a minimum value that is enough to allow the controller to track large process variable offsets, but at a very low speed of response. In a particular real time test on a live dosing rig, the response to a closed loop step test using a standard PI controller with a low gain took more than four hours to be completed due to the sluggish response of the controller.

## 5. IMPLEMENTATION AND TESTING

The water industry like most other process industries uses a combination of conventional analogue (4 – 20 mA) instruments and actuators with digital control PLC's, which nowadays have the resolution that allows them to control continuous processes. That said, PLC's still have their limitations when it comes to the implementation of advanced control methods as they seem to lack some important functionalities needed for continuous process control. It was also noticed with this particular application that offsets in the analogue modules interfacing between the PLC and the equipment (water flow meter, Chlorine analyser, and Chlorine dosing pump) can either exaggerate or dampen signals to and from the controller respectively. It is therefore important to obtain a process model that is a valid representation of the actual process so that the effect of the above mentioned offsets will be minimal; otherwise, those offsets will add to the uncertainties caused by the mismatch between the actual process and the process model and make the control system design process much more complicated.

The control algorithm was written in PLC ladder logic. Therefore, all continuous functions and the process model had to be written in that form. The dead time was then implemented using a data array that stores data in sequence at a frequency that is equal to the process sampling frequency, and the length of this array is equivalent to the predicted process dead time. To be able to test the Smith predictor for different flow rates, the control algorithm included functions to calculate the process parameters from online water flow rate measurements, and update the process model as well as the length of the delay array accordingly. There is also a tuning routine that uses the minimisation of the Integral of Absolute Error (IAE) tuning method to calculate the PI parameters (Kc and Ti). Many tuning methods have been suggested for Smith predictor applications, and many of them seem to have produced a robust performance [3, 5-8]. The following equations provide a good starting point for the minimum IAE method which is used to obtain the optimum PI parameters:

$$Kc = 0.984/Kp*(\tau/Td)^{0.986} \quad (2)$$

$$Ti = \tau/0.608*(Td/\tau)^{0.707} \quad (3)$$

Where Kc is the controller gain, Kp is the process gain, $\tau$ is the process time constant, Td is the process dead time, and Ti is the controller integration time. To make the controller self-tuning, these formulae were written in the control algorithm, and as part of the cyclic scan sequence, the PLC would calculate the process parameters based on the online flow rate measurement, then calculate the PI parameters as shown above and update them in the PI controller function block instantly. The following plot of real time data of closed loop step tests of the Smith predictor as explained above also shows the effect of sudden variation in the water flow rate on the process:

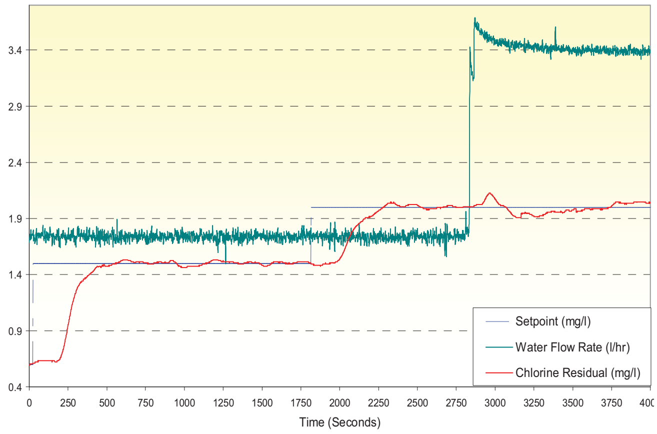


Fig. 6. Setpoint tracking performance of the Smith Predictor and its response to a major (Flow rate) disturbance.

The response achieved here conforms to the simulation results in terms of setpoint tracking, stability of the system, and the speed of its response. Also, the disturbance caused by the change in water flow rate did not have a significant effect on the process dynamics. The same test rig was used to test the same process under the same operating conditions using just a tuned PI controller in order to compare it to the performance of the Smith predictor, and the response is shown below.

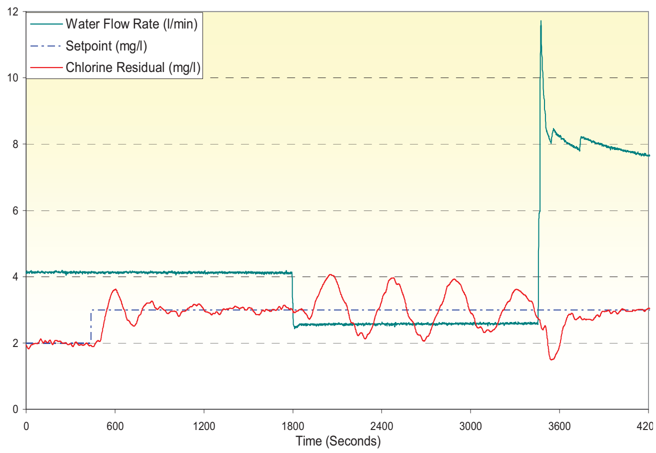


Fig. 7. Performance of a PI controller at various water flow rates.

The controller here was tuned well enough to produce an acceptable performance at a medium flow rate of 4.2 l/min, but when the flow was reduced to about 1.7 l/m, the controller became incapable of keeping the process variable at steady state until the flow was increased to a much high rate, where the controller slowly tracked the setpoint. Retuning the controller at this flow rate, would produce a faster response than the response shown, but at the low flow rate, the only option was to detune the controller (by keeping the controller gain as low as possible) so that it will respond to the step input, but at a relatively low speed of response, and hence not causing the oscillations seen in figure 7.

It is important to emphasise that without an accurate process model, the Smith predictor performance deteriorates. During this trial, initially the dead time was under estimated by around 20% and as a result the controller reacted earlier than required causing an overshoot in the Process variable of nearly 15%.

## 6. CONCLUSION

Simulation of PI controllers on FOPDT processes shows that the performance of the PI controller is dependent on the process dead time. In this trial the PI controller was found incapable of handling very long time delays regardless of the method used to tune it. The Smith predictor provides a reliable solution as long as the process model used is an accurate estimation of the actual process. In challenging process control applications where the process is time varying, adaptive Smith predictor configurations can be used effectively to overcome the uncertainty caused by the changes in process dynamics. Simulations and practical tests have shown that this method can be implemented successfully in water treatment processes.

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