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Applications of automatic control systems for chlorination and dechlorination processes in wastewater treatment plants

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Abstract

Due to recent requirements by the U.S.E.P.A. towards the standards on chlorine residuals for chlorination and dechlorination processes, together with the commitment to optimize the process operating conditions for chemical cost savings and to let the plant operator have more time working on other important projects, the City of Houston has been utilizing automatic control systems (Programmable Logic Controllers) at over twenty WWTPs to meet the above tasks. This paper will present one of the City's WWTPs which implemented the auto-control system. It also discusses how to solve the problems of noises in instrumentation signals and dead time which are common in auto-control systems. Finally, it will show how much success the system has complied with the U.S.E.P.A.'s requirements and effectively reduced the chemical costs.

Keywords: Chlorination; Dechlorination; Programmable logic controller; Feedforward-feedback-multivariable controls; Relay control mode; PID control mode; Special function program control mode; Disturbance; Noises; Average estimator; Lag time (dead time); Time constant; Historical trendings; Efficiency; Data analysis; Transfer function

1. Introduction

Beltway WWTP has an average flow of 5.0 MGD. The effluent from the clarifier has to pass through a chlorination and dechlorination tank before being discharged into the outfall. Starting in 1990, in terms of chlorine residuals, the U.S.E.P.A. required the City's WWTPs to comply with the following specifications: the chlorine residuals for samples before and after the dechlorination location (weir location) be above 1.00 ppm and below 0.10 ppm, respectively. Without auto-control system, the plant operator has to go through the following tedious procedures:

1. collect the pre-weir and post-weir samples for chlorine residual information;
2. read the water flow;
3. calculate how much sodium-hypochlorite (or chlorine) feed rate there should be in order to meet the pre-weir chlorine residual requirement;
4. calculate how much sodium-bisulfite feed rate there should be in order to meet the post-weir residual requirement;
5. estimate the actual feed rates there should be at that time based on previous experiences on the process lag time;

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6. carry out the sodium-hypochlorite and sodium-bisulfite chemical feedings,
7. repeat steps 1–6 as often as possible.

The City has utilized an auto-control system to relieve the operator from the above tedious tasks. The auto-control system runs twenty four hours a day and seven days a week (instead of 8.0 hrs/day and 6.0 days/week if run manually by the operator), and it operates very effectively and efficiently.

2. Chlorination and dechlorination auto-control systems

A schematic diagram in Fig. 1 shows the overall relationship amongst the chlorination tank, the auto-control system and the associated instrumentation.

The chlorination tank consists of three regions: the mixing (or injection), contact (or chlorination) and dechlorination regions. In the mixing region, the influent will be mixed with the chlorine at the injection point A. The nearby submersible pump at point B will continuously pump the chlorinated sample in this area to the chlorine analyzer for chlorine residual measurement. In the contact region, air diffusers are used to mix chlorine with water and to add oxygen into water. In the dechlorination region, two submersible pumps at points C and D (one before and one after the weir, respectively) will continuously pump the samples to the analyzers for residual measurements. Sodium-bisulfite (NaHSO3) chemical will be distributed along the weir for dechlorination. The flow of the effluent is measured by a pressure sensitive transducer located in front of the weir.

The auto-control system consists of a TI-545 Programmable Logic Controller (PLC) and three HACH-CL17 chlorine analyzers. The PLC can receive and transmit multivariable signals from and to the field. The chlorine analyzers receive the samples from points B, C and D for chlorine residual measurements. The major process (controlled) variables to be controlled are the chlorine residuals at the injection, pre-weir and post-weir points. The required residuals at these points are about 3.50 ppm, above 1.00 ppm and below 0.10 ppm, respectively. The major manipulated vari-

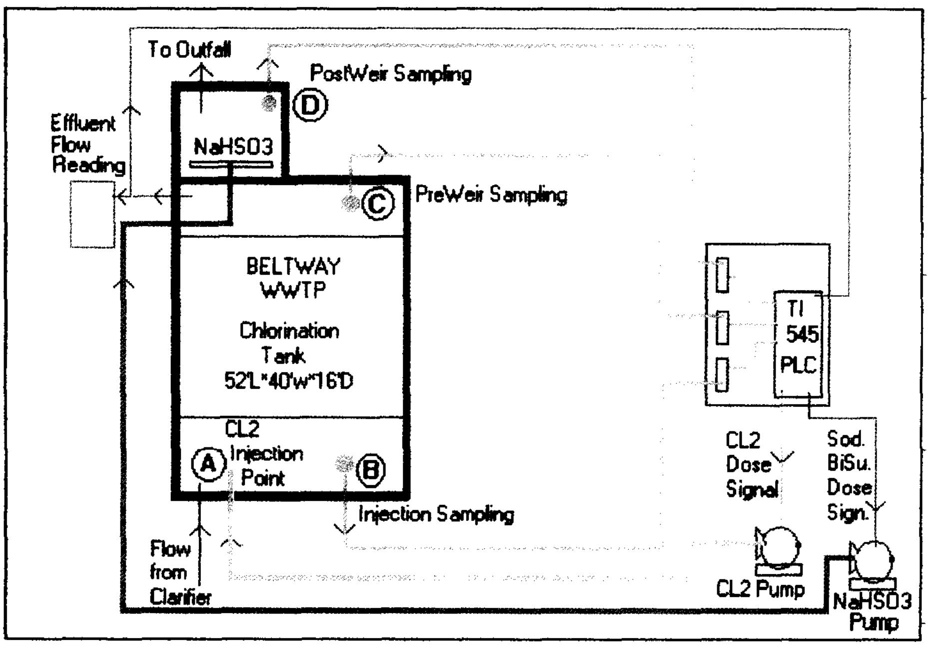

Fig. 1. Beltway chlorination and dechlorination auto-control system.

ables are the PLC's outputs to the chemical pumps which change the chemical feed rates to the field. The relay ladder logic program used in the PLC is TISOFT, the data acquisition program is TIDAC, and the data analyzing program is LOTUS-1-2-3.

The associated instrumentation consists of three submersible pumps, two sodium-hypochlorite (bleach or chlorine) pumps, two sodium-bisulfite pumps, a pressure-sensitive flowmeter, three suspended solids filtering devices, and related pipings. The submersible pumps will send the samples at points B, C and D to the chlorine analyzers. The chemical pumps will receive the signals from the PLC and send out the necessary chemical feed rates to the field.

3. Modes of control

3.1. Feedback using PID control mode

A simplified diagram at the injection area and associated devices is shown in Fig. 2.

The clarifier's effluent arrives at the chlorination tank via an underground pipe near point A. The flow will be mixed with chlorine at point A where the injection of chlorine is made by the CL2 pump. At point B, a submersible pump inside the screening bucket (the bucket screens out the suspended solids) will pump the chlorinated water sample to the CL17 analyzer for the determination of the chlorine residual at this sampling point. For terminology simplification, the chlorine residual at this sampling point is called the injection (or mixing) residual. Before entering the analyzer, the sample is further filtered (to remove tiny suspended solids and algae) by two more filter elements (one coarse and one fine). It takes two and half minutes for the CL17 analyzer to finish the analyzing procedure and to give the chlorine residual result to the TI-545 PLC via an electrical signal. The PLC then compares the received chlorine residual with the setpoint, performs some calculations based on the controller PID-loop tuning constants set by the engineer, and sends out an appropriate chlorine dosage via an electrical signal to the chlorine controller panel. The controller panel will convert the received signal into an appropriate mechanical action in the chemical pump to decrease or increase the chlorine feed rate towards the injection point. The PLC's PID-loop program generally works well. If the received injection

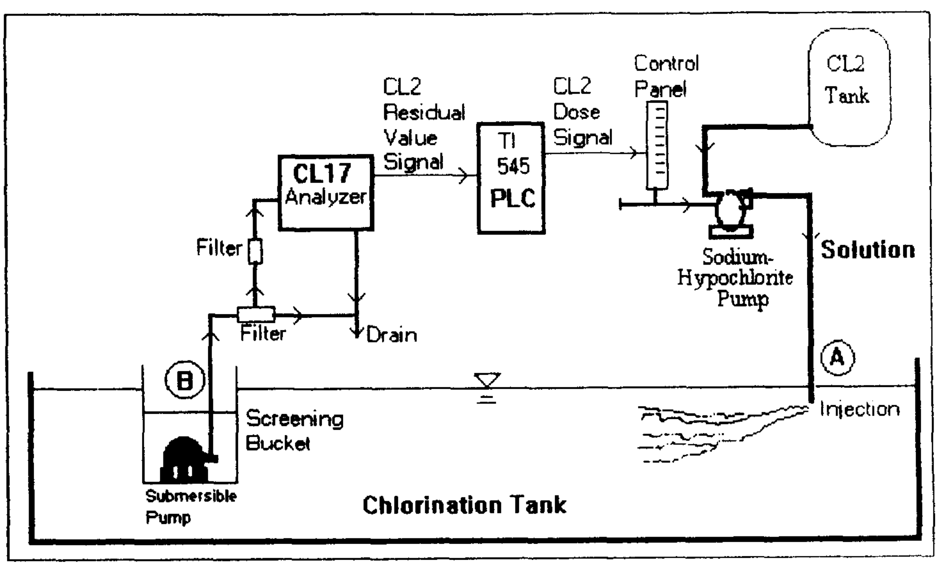

Fig. 2. Chlorine injection area and associated devices.

residual is below the setpoint (i.e., 3.50 ppm), the PLC will send a higher signal to the chlorine controller panel to increase the chlorine feed rate, and vice versa.

3.2. Feedback using relay control mode

Sometimes, in order to fine tune the PLC for better PID-loop tuning constants after a change in the process characteristic or to bring an unstable loop into normal operation, the engineer uses the relay control mode (Astrom and Hagglund procedure) instead of the said PID control mode. Another method to obtain the PID-loop tuning constants and the process characteristic parameters such as dead time and time constant is to apply the open-loop step input (Ziegler and Nichols procedure) method (taking the advantage of the constant water flow in some period of time). Both procedures have given satisfactory results. Fig. 2 is a schematic diagram of the feedback control using a PID-Loop algorithm.

3.3. Feedforward and feedback using SFPGM control mode

For the dechlorination process, both feedback and feedforward control modes are implemented. Based on the values of the effluent flow (at location near point C) and chlorine residuals at pre-weir and post-weir locations (points C and D in Fig. 1) which were received by the PLC, a special function program (SFPGM) in the PLC will calculate the sodium-bisulfite feed rate required to keep the post-weir residual below 0.10 ppm. The value of the sodium-bisulfite feed rate is a function of the effluent flow, the chlorine residuals at pre-weir and post-weir locations, and the sodium-bisulfite concentration. The top left part of Fig. 1 is a simplified schematic diagram of the dechlorination area together with its associated devices. Two submersible pumps at points C and D will pump the samples (pre-weir and post-weir) to two CL17 analyzers for residual measurements. The values of the effluent flow reading, pre-weir residual (feedforward) and the value of the post-weir residual (feedback) will be sent to the PLC as inputs. The PLC's output will control the chemical pump feed rate of sodium-bisulfite ($NaHSO_3$) to the weir which located between point C and point D.

4. Operations

4.1. Data analysis preparation

One of the main objectives of the auto-control system is to keep the chlorine residuals within specifications. This means that the pre-weir and post-weir chlorine residuals need to be above 1.00 ppm and below 0.10 ppm, respectively, regardless of any disturbances to the process. The major disturbance to the chlorination and dechlorination processes is the water flow. Another quite important disturbance is the chlorine demand which is a function of the flow and the ammonia content in the water. Had the flow and chlorine demand been constant, then there would be no need for auto-control system. Both disturbances are functions of time.

The flow through the chlorination tank is continually changing with different amplitudes and frequencies. The rate of on/off operations of the submersible pumps at the wet wells and the combined capacity of the aeration, reactor, clarifier and chlorination tanks will result in knowing how much the amplitude and frequency of the flow will change. Sometimes, the change in amplitude is so small in a period of several hours that the flow can be assumed to be constant during this period. The major problem in identifying the actual flow by the pressure-sensitive-transducer flowmeter is the fluctuations in readings due to the rippling of the water waves (physical noises) and due to the electrical noises of the instrument. One method of reducing these physical and electrical noises is the average estimator technique. For example, without averaging, the measured data for the flow at Beltway are fluctuating with about 150.00% difference between two consecutive flow data in an interval time of 2.5 minutes. Taking an average estimator of eight consecutive flow data will result in a fluctuation of about only 5.00% difference between two consecutive flow data in an interval time of 2.5 minutes. The use of this averaging method has been very helpful in analyzing the collected data and in better controlling the feedforward control mode.

Another major problem in interpreting the data is the process dead time and the time constant. The process dead time (sometimes called lag time, pure delay time, transport time) is the time required for the chlorine to travel from the injection point A to the sampling point B. The total dead time for the chlorination auto-control system is the time between the initiation of an input change in chlorine dose and the detectable responding change of the residual output. The process time constant is the time required for the chlorine residual to reach 63.2% of the total change after a step input chlorine dose is made. Rearranging or changing the relative locations amongst the flow inlet pipe, the injection point A, the mixing intensity, the sampling point B and the air diffusers can result in a higher or lower dead time and time constant. The auto-control system works best at the lowest process dead time and time constant. In systems with large dead time or time constant, the data on historical trending graphs often confuse or mislead the inexperienced investigators or analysts. For example, in almost one hour, a continuous historical trendings chart recorder may show that the chlorine residual is decreasing while the chlorine feed rate is increasing (at constant water flow and chlorine demand). This is because the lag time is one hour for this particular process. Had the investigator collected the data for a period of several hours, he would have noticed this lag time characteristic of the process. When analyzing a historical trendings diagram, therefore, the investigator should keep in mind the effect of process dead time and time constant so that the interpretation of the data can be meaningful and explainable.

4.2. Field data analysis

Both the feedback and the feedforward auto-control algorithm of the chlorination and dechlorination processes at Beltway WWTP work well. The injection residuals vary from 3.0 to 4.00 ppm, its setpoint is 3.5 ppm. The pre-weir residuals vary from 1.0 to 1.6 ppm. The post-weir residuals are all below 0.10 ppm. The PLC records in its memory the following variables: Time (second),

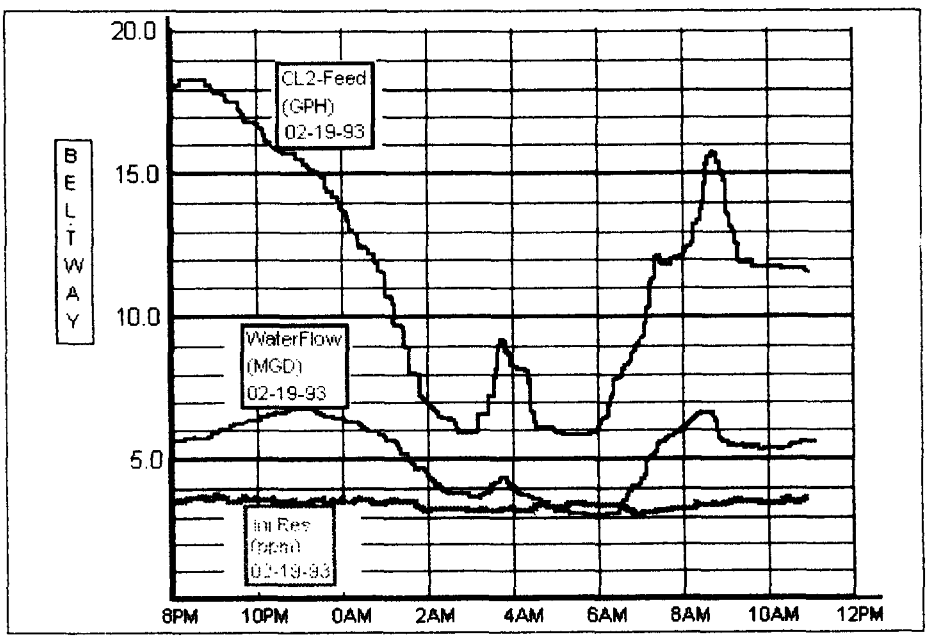

Fig. 3. Feedback auto-control field data at injection point on test date #1.

Chlorine Residuals (ppm) at Injection, Pre-Weir and Post-Weir locations, Wastewater Effluent Flow (MGD), Sodium-Hypochlorite (or Chlorine) Feed Rate (GPH), and Sodium-Bisulfite Feed Rate (GPM). The variable data can be retrieved using TIDAC software and imported into LOTUS-1-2-3 for analysis.

The historical trendings diagram (reproduced from the LOTUS-1-2-3 graph) in Fig. 3 shows the result of the feedback auto-control operation near the injection point at Beltway WWTP on test date #1 (02-19-93). While the sampling interval time is 2.5 minutes, the diagram represents about 384 data for each variable. The injection residuals are well under control and quite close to the setpoint of 3.5 ppm. In this feedback auto-control, the only input to the PLC's PID-Loop is the injection residual (ppm) and the only output is the chlorine feed rate (GPH). It is noted that the controller has responded very well with the changes in water flow and chlorine demand to keep the injection residual close to the setpoint.

In order to determine the efficiency and the effectiveness of the auto-control system, let us assume that the chlorination and dechlorination processes were run manually. At 8 PM, the operator set the chlorine feed rate at 18.0 GPH and went home to rest. When he came back to work the next day at 8 AM, what had happened when he was absent in the last 12.0 hours?

Due to the changes in the flow and chlorine demand, the chlorine consumption could have been reduced in an amount of about 44.0 gallons (area enclosed by the 18.0 GPH horizontal line, the 8AM vertical line and the CL2-Feed curve). In those 12.0 hours, the manually operated plant would use about 144.0 gallons of sodium-hypochlorite chemical, while an auto-control operated plant would use about 100.0 gallons of chemical; this represented a 30.0% savings in sodium-hypochlorite chemical cost in one night.

Furthermore, as seen in Fig. 3, if the chlorine feed rate were at 18.0 GPH at 2 AM, for instant, then the injection residual could have been a lot above the desired value of 3.5 ppm. This would affect and increase the pre-weir residual and result in another increase in sodium-bisulfite chemical cost. Since the operator was not available in the plant at 2 AM to increase the sodium-bisulfite pump rate for dechlorination of the excess pre-weir residuals, the post-weir residuals, therefore, could be increasing to the values

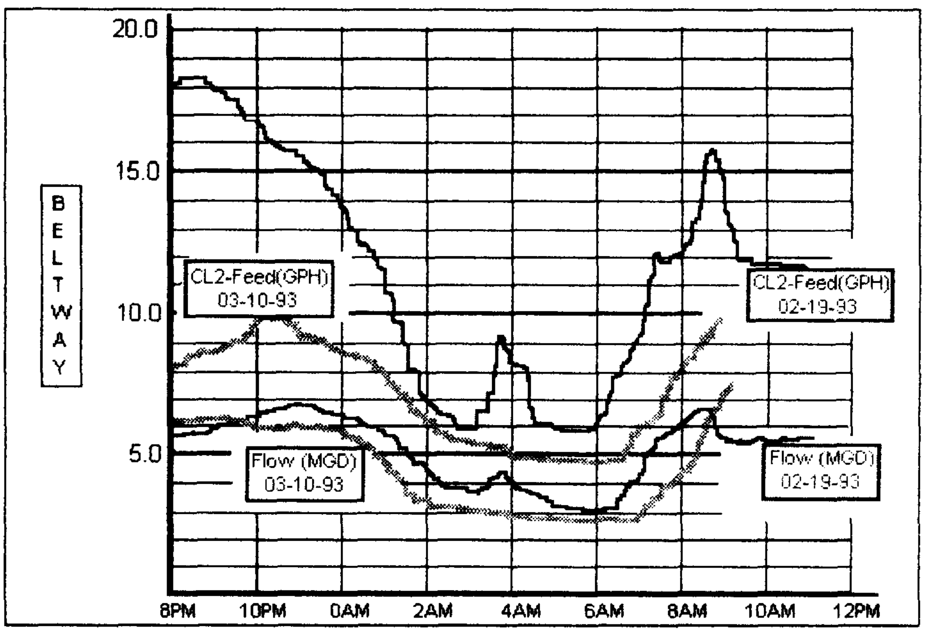

Fig. 4. Feedback auto-control field data at injection point on test dates #1 and #2.

above 0.10 ppm. A permit violation could occur if this happened.

Another example on data analysis for the auto-control system at Beltway WWTP is shown in Fig. 4 which is the historical trendings diagram on the same time scale of the water flows and the chlorine feed rates at Beltway on test date #1 (02-19-93) and on test date #2 (03-10-93). The diagram shows that, at similar water flow (the chlorine injection, pre-weir and post-weir residuals (not shown in the diagram) on both days were within the desired specifications) the chlorine consumption on 03-10-93 was a lot less than that on 02-19-93. This reduction in chlorine consumption might either be due to the ammonia and the total suspended solids concentrations in the water, or to the ambient temperatures, mixing intensity, aeration, contact time, etc. Below are some field data collected, analyzed and recorded by the 69th Street Laboratory on those two days:

Date	Temp.	TSS (ppm)		Ammonia (ppm)	
	(degree C)	Raw	Effluent	Raw	Effluent
02-19-93	20.2	156.0	6.00	20.0	0.10
03-10-93	20.7	120.0	9.00	16.4	0.30

As can be seen from the above data, more ammonia had to be removed on 02-19-93, therefore, more chlorine was consumed compared with that on 03-10-93 as shown in Fig. 4. The higher TSS in the effluent on 03-10-93 might be another factor in the decrease of chlorine consumption.

In other words, Fig. 4 shows the effects of chlorine demand (due to changes in ammonia and TSS in water) upon chlorine consumption when there is no disturbance in flow. For example, at 9:30 PM while the flows on both days are at 6.2 MGD, the chlorine consumption on 02-19-93 (17.0 GPH) is higher (due to higher chlorine demand) than that on 03-10-93 (9.0 GPH).

5. Transfer function

One of the important tools in the understanding, analyzing and designing an auto-control system is the application of transfer functions. A process (or controller) transfer function is defined as the frequency-domain ratio of the output of a process (or controller) over its input, with all initial conditions set to zero. It can be obtained

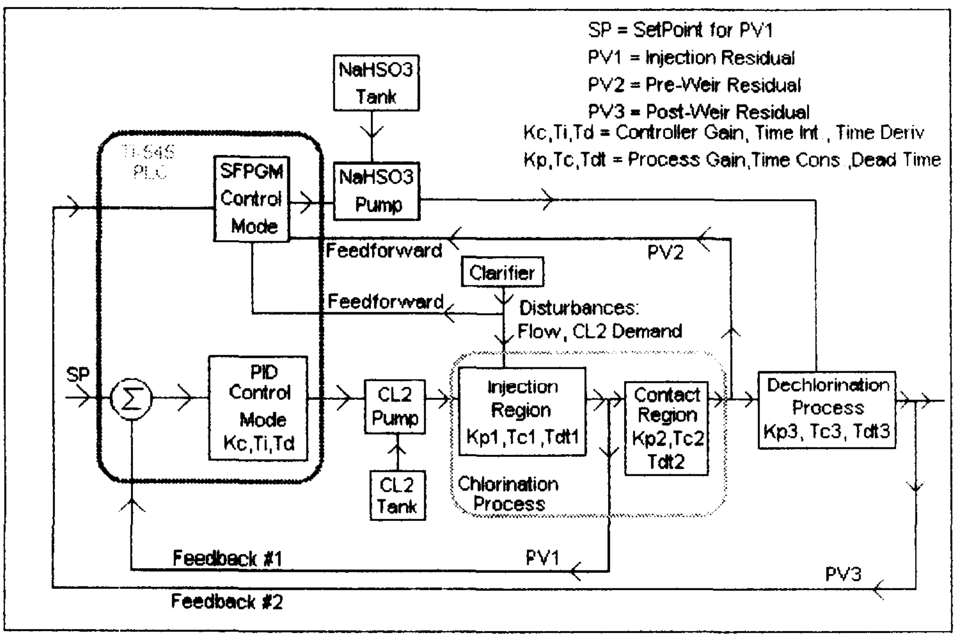

Fig. 5. Feedback-feedforward-multivariable auto-control system.

either by using a frequency-domain mathematical tool (Laplace transformations of time-domain algebraic equations) or by using an open-loop step-input (or Ziegler and Nichols) method. The Z-N method is more popular and accurate than the mathematical method due to its ease of implementation. From the transfer function, a time-domain equation that describes the output of a system in terms of its input can be derived. A transfer function is also helpful in finding if the control system is stable when the input to the system has a certain magnitude and frequency. This topic can be found in several current control system textbooks. The simplified schematic diagram in Fig. 5 briefly shows the overall feedback-feedforward-multivariable auto-control system in the chlorination and dechlorination processes discussed so far. If the process characteristics can be identified, then a transfer function can be derived.

For example, for the chlorination process in Fig. 5, after the process gain Kp1, the time constant Tc1 and the dead time Tdt1 were identified by the historical trendings diagram from the step-input open loop test, a simplified first order transfer function (TF1) can be written as follows:

$$\frac{\text{Output}(S)}{\text{Input}(S)} = \text{TF1} = \text{Kp1} \times \exp\left(\frac{-\text{Tdt1} \times S}{\text{Tc1} \times S + 1}\right),$$

where S is the frequency-domain operator.

Taking the inverse Laplace transformation of TF1 will result in the equation that shows the relationship between the output and the input in the time domain. The output (t) is the Chlorine Injection Residual in ppm and the input (t) is the CL2 Dose in GPH.

6. Summary

The applications of automatic control systems for the chlorination and dechlorination processes in wastewater treatment plants have helped the City of Houston to comply with the U.S.E.P.A. requirements, to reduce the chemical costs, and to operate the plants efficiently and effectively. A knowledge in averaging estimator, dead time and time constant can help to analyze a complicated field historical trendings data caused by excessive noise interferences. An auto-control system also continually shows the effects of disturbances in flow and chlorine demand upon chemical consumption. A process transfer function can help to find the time-domain equation of the process variables in terms of chlorine dose input, and to determine whether a system is stable when an input or disturbance occurs at a certain magnitude and frequency.

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