CONTROLLER PERFORMANCE ASSESSMENT

Through Stiction in Control Valves in a Process Control Class

Ranganathan Srinivasan, Raghunathan Rengaswamy, and Sandra Harris
Clarkson University • Potsdam, NY 13699

Industrial surveys[1–3] in the last decade have indicated that only about one-third of industrial controllers provide acceptable performance. Performance demographics of 26,000 PID controllers, collected across a wide variety of processing industries in a two-year time span, indicate that the performance of 16% of the loops can be classified as excellent, 16% as acceptable, 22% as fair, 10% as poor, and the remaining 36% are in open loop.[3, 4] Since PID controllers constitute 97% of all industrial controllers, poorly performing loops pose significant problems with huge financial implications. Hence, controller performance assessment (CPA) is an important area that is worthwhile to introduce in undergraduate process control curriculum. There are a number of articles that have discussed approaches for introducing control advances made in multivariable, nonlinear, and distributed parameter systems in the undergraduate curriculum.[5–9] This article proposes the introduction of CPA in an undergraduate classroom through the use of a nonlinear phenomenon in control valves that leads to oscillations.

Performance degradation in control loops manifests itself as: poor set point tracking, poor disturbance rejection, excessive final control element variation, or oscillations in measurement signals. Sustained oscillations in control loops can be due to multiple reasons:

1. *Valves with high static friction (also known as stiction). Presence of dead band and hysteresis in valves*

Ranganathan Srinivasan *received his B.E. in electronics and instrumentation engineering from Annamalai University, his M.Tech. in systems and control from IIT Bombay, and his Ph.D. in chemical engineering from Clarkson University. He currently works for Honeywell Automation and Control Labs in Phoenix, and is actively pursuing research in the areas of Loop Performance Monitoring and Nonlinear Control Strategies.*

Raghunathan Rengaswamy *is an associate professor in the chemical and biomolecular engineering department at Clarkson University. He received his B.Tech. from IIT Madras and his Ph.D. from Purdue University, both in chemical engineering. His research interests include Fuel Cells and Process Systems Engineering.*

Sandra L. Harris *is an associate professor in the Department of Chemical and Biomolecular Engineering at Clarkson University. She received her B.S. and M.S. from MIT, and her Ph.D. from UCSB, all in chemical engineering. Her research interests are in the areas of Process Control and Identification.*

can also cause limit cycles in integrating processes.

2. *Poorly tuned controllers in nonlinear processes with varying gain.*
3. *Insufficient digital resolution (quantizing effects in data acquisition cards).*
4. *Controller saturation.*
5. *Oscillations that are external to the loop.*
6. *A combination thereof.*

Reasons for oscillations are summarized in Figure 1.

CONTROLLER PERFORMANCE ASSESSMENT

In industrial controllers, routine operating data archived for each PID loop includes—but is not limited to—Controller Output (OP), Process Output (PV), Set Point (SP), loop type, and controller settings. This archived data can be used to identify potential areas of improvement, trends, and problems in an incipient fashion for preventative maintenance. As mentioned before, industrial surveys over the last decade have indicated that the performance of nearly two-thirds of all controllers can be improved. In light of this, as envisioned by Kozub[10] and many others, several CPA tools that can automatically detect, diagnose, and, if possible, improve the performance of problematic control loops are being developed (see Reference 11 for a survey and analysis of commercial products being developed). A specific set of requirements for such CPA tools from the authors' perspective is listed below:

1. *Automated computation procedure that can evaluate approximately 1,000 loops or more a day.*
2. *The CPA tool must use noninvasive techniques.*
3. *Minimal use of process knowledge, as it might be infeasible to build or maintain a knowledge base for several thousand loops.*
4. *Acceptable false alarm and detection rates.*
5. *The algorithms used must be theoretically sound, modestly complex, and efficient.*
6. *Problem loops should be detected and reported using routine operating information.*
7. *It should be possible to diagnose the possible cause(s) for performance degradation.*
8. *Suggest and implement corrective action (where applicable) to mitigate the cause of poor performance.*

Objectives 1, 2, 3, 5, and 6 have been adequately addressed using information technology and advanced computational platforms. Statistics for objective 4 have not been reported in the open literature to date. Objective 7, *i.e.*, diagnosing the cause for poor performance, has received considerable attention recently.[12–24]

Most present-day CPA tools assess control loop performance using some variant of the Minimum Variance Control (MVC)[25] concept. In this approach, the minimum error (between the set point and the measurement) realizable by any controller is bounded by the performance of the MVC. Harris[26] showed that a lower bound, on a closed-loop output variance realized using MVC, can be obtained by analyzing routine operating data, provided the process dead time is known *a priori*. A normalized index for assessment of feedback controller performance determined against a benchmark of MVC was then introduced by Desborough and Harris.[27] The normalized controller performance index is given below:

$$\zeta(b) = 1 - \frac{\sigma^2_{mv}}{\left[\sigma^2_y + \mu^2_y\right]} \qquad (1)$$

where σ^2_{mv} is the output variance that can be achieved using MVC calculated by solving a system of linear equations generated based on a dead time b; σ^2_y is the variance of measured output; and μ^2_y is the mean-squared deviation from the set point. The index ζ(b) is bounded by [0, 1], while $\zeta \approx 0$ indicates the best achievable performance, *i.e.*, minimum variance control, and $\zeta \approx 1$ indicates poor performance, showing that retuning of the controller may be necessary. Over the last decade, there have been a number of other academic investigations on the development of robust performance indices.[11]

While the normalized index can be used to identify poorly performing loops, it provides very little diagnostics toward ascertaining the root cause of oscillations. In addition to this, a process engineer (or control engineer) responsible for more than 400 loops[3] may not have the time to diagnose the problem and improve each poorly

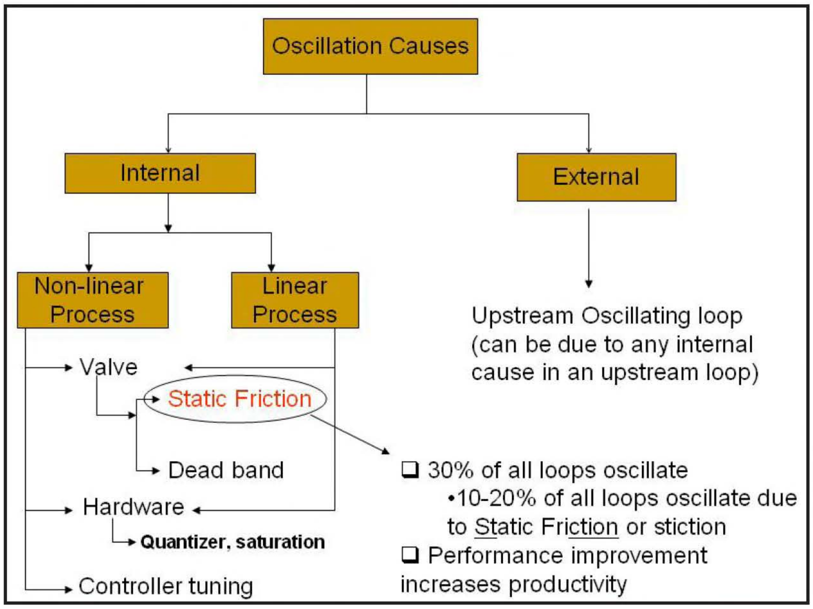

***Figure 1**. Common causes for control-loop oscillations.*

Teaching stiction in undergraduate classes has a number of advantages. Other than its obvious importance, teaching stiction helps introduce the concept of CPA to undergraduate students.

performing loop. Hence, it may not be possible to choose an appropriate corrective action just based on performance indices alone. The last decade has seen an increasing interest in the area of detecting and diagnosing the cause of oscillation.[12–24]

The last objective, *i.e.*, suggesting corrective action, is gaining importance. Corrective actions can include: identifying new controller parameters,[28] valve maintenance or stiction compensation,[29, 30] eliminating upstream disturbances, or a combination thereof.

Focus of This Article

It has been reported that 20% to 30% of all control loops oscillate due to valve problems caused by static friction (also called stiction).[1, 3] Stiction is a real industrial process control problem. Teaching stiction in undergraduate classes has a number of advantages. Other than its obvious importance, teaching stiction helps introduce the concept of CPA to undergraduate students. Stiction phenomenon can also be used to introduce nonlinear behavior, such as limit cycles, over and above the usual linear analysis taught in a control curriculum. Finally, thinking about controller tuning with stiction will force the students to think harder, broadening their understanding of control concepts. For example, in traditional control thinking high gain is the usual suspect for causing oscillations. Whenever there are oscillations, control engineers are taught to reduce the gain. For stiction-related oscillations, reducing the gain can actually make the oscillations worse. Therefore, this experiment can be used to make the students think about control more carefully to prevent these mistakes.

CONTROL VALVE AND STICTION PHENOMENON

A control valve consists of two main parts: a valve; and an actuator that forces the stem to move. Additionally, it may contain a positioner that controls the valve stem, allowing it to correspond with the control signal. Stiction in control valves is thought to occur due to seal degradation, lubricant depletion, inclusion of foreign matter, activation at metal sliding surfaces at high temperatures, and packing around the stem. The resistance offered from the stem packing is often cited as the main cause of stiction. Stiction happens where static friction is substantially higher compared with dynamic friction. There is an initial phase where the valve fails to respond to the control signal until the static friction is overcome. Once the static friction is overcome, as friction reduces to the dynamic friction level, the valve slips suddenly. It may then stick at the new position or follow the control signal. This stick-slick behavior causes oscillations (limit cycles) in both the process variable and control signal.

In the following sections, a simulation and an experimental case study are described to illustrate the effect of stiction phenomenon in control loops.

SIMULATION CASE STUDY

Figure 2a shows a basic regulatory control loop, and Figure 2b shows the loop structure in the presence of stiction. The identification of a plant's linear dynamics (either in open or closed loop) includes valve dynamics (see G_p in figure 2a). Valve dynamics are observed only after the start of stem movement; stiction phenomenon, if present, precedes valve dynamics. This is represented in Figure 2b.

Several models for stiction have been proposed in the literature.[31, 32] Here, we consider a simple stiction model parameterized by one parameter, "d," given by Eq. (2).

$$x(t) = \begin{cases} x(t-1) \text{ if } |u(t) - x(t-1)| \le d, \\ u(t) \quad \text{otherwise} \end{cases} \tag{2}$$

Eq. (2) is characterized by a single parameter, "d," termed as stiction band. Here x(t) and x(t − 1) are present and past

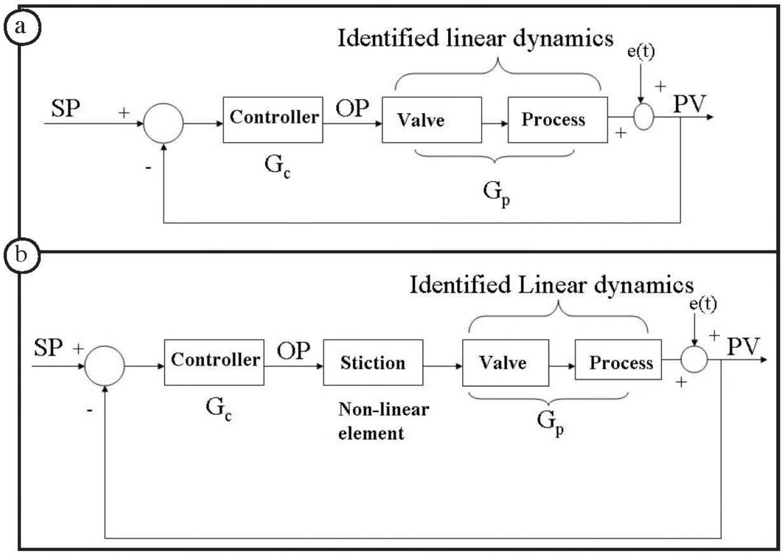

***Figure 2**. (a) Regular process control loop. (b) Process control loop in presence of stiction.*

stem movements and u(t) is the present controller output. The stem moves from one position to the other once it overcomes the dead band "d."

In the process industries, stiction measurement is done when the loop is in manual mode. A slow, increasing ramp-type control signal is given as valve input. The valve input is increased until a noticeable change in the process variable is observed. Stiction is reported as a percent of the valve travel or span of the control signal. The stiction model given by Eq. (2) coincides with the procedure used for measuring stiction and is reported as the span of the control signal. Readers are referred to Srinivasan, *et al.*,[23, 24] for a detailed discussion on the applicability of this simple model for modeling stiction.

A continuous system, $\frac{1}{s+1}$, with a discrete PI controller ($K_c = 0.4$, $\tau_i = 1$) was considered. The sampling time (T_s) was fixed to 0.1. A simulation setup in MATLAB was designed using the simple stiction model [Eq. (2)]. This is shown in Figure 3.

Simulation was carried out for 100 seconds, with a sampling time of 0.1 seconds. To induce limit-cycle behavior, however, a small deviation from the steady-state is necessary and was given. Figure 4 shows the control loop data when subjected to a stiction measure of d = 0.1. While we used an experimental setup at Clarkson University for teaching stiction, the simulation case study presented here could be used instead of the experimental setup, if such a setup is unavailable.

EXPERIMENTAL CASE STUDY: LIQUID-LEVEL SYSTEM

Figure 5 depicts the liquid-level system at Clarkson University. It is a water-flow system with a linear needle plug valve assembly. The actuator is configured to "Air to Close" with "Fail to Open" settings. The installed control valve does not have a positioner. The level measurement (PV) is acquired in the computer using a Data Acquisition card (PMD-1208LS). The level control was accomplished with a PI controller implemented in Matlab (Simulink) environment with a sampling time of 0.5 seconds. Simple step tests in control signal indicated a first-order linear process with a gain ($K_p = -4.5$) and approximate time constant (τ_p = 80 seconds). The parameters of PI controller were $K_c = 0.88$, $T_i = 0.0138\ \text{sec}^{-1}$, obtained using the IMC rule for filter-parameter $\lambda = 4$. The control valve exhibited negligible static friction (< 0.1%). There are several ways the stiction phenomenon can be demonstrated on this setup. The static friction in the control valve can be increased by tightening the packing around the stem. This will introduce stiction in the control valve. We have done this, and made extensive use of such data in our research work. While this is possible, if the experiment is going to be used for an undergraduate lab, tightening the stem might not be necessary. Continuous tightening and loosening of the stem might damage the packing, leading to valve replacement. It is sufficient to use a stiction model in the Simulink environment. A Simulink implementation of the whole system is shown in Figure 6.

STUDENT EXERCISE

The stiction experiment was assigned as a project to a group of students who took the process control course taught by Professor Sandra Harris. A detailed instruction sheet on how to operate the liquid-level system and Matlab interface (in-

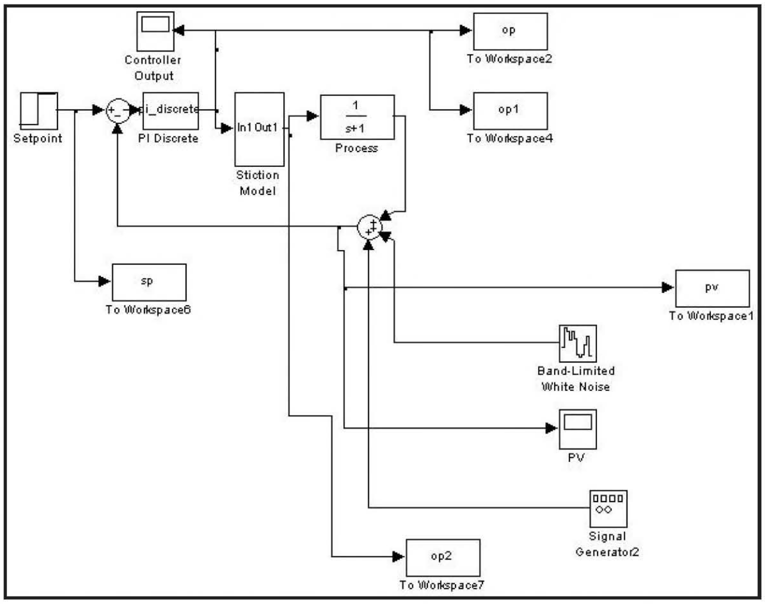

Figure 3. *Simulation case study implemented in MATLAB.*

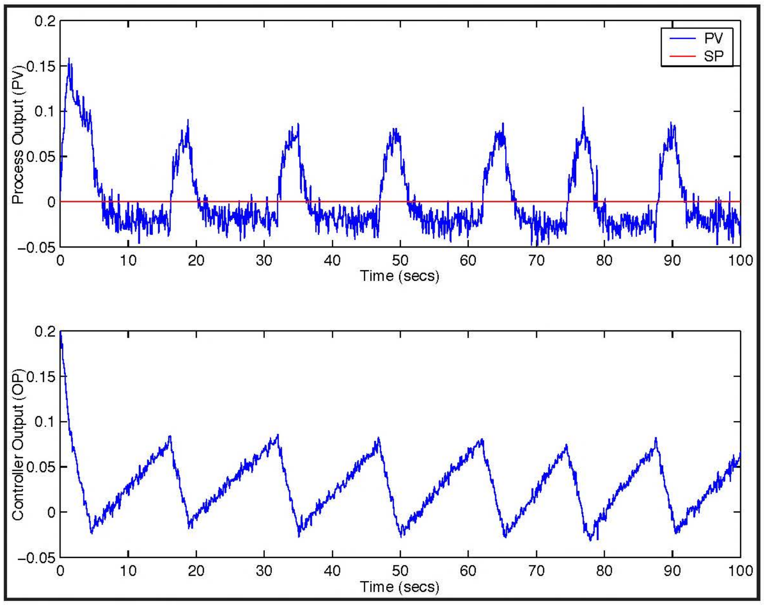

Figure 4. *Loop data when stiction band d = 0.1.*

cluding how to incorporate stiction) was provided to students. They were then asked to work the experiment and answer the following questions:

(1) *Bring the process to a steady state (say Level Set point = 30%) using closed-loop computer control with a stiction band of d = 0%.*

(2) *Set the stiction band to d = 4%.*

(3) *Give a step change of 10 %,* i.e., *the Level Set point is changed to 40.*

(4) *Observe the measurements for 15 minutes. Explain why the data oscillates.*

(5) *Change the controller settings (Note this time instant).*

  (a) Increase the Integral gain (equivalent to reducing the value T_i*) and observe the data for 10 minutes. Comment on oscillation period and amplitude.*

  (b) Reset the integral gain to its original value. Increase the controller gain, K_c*, to a new value. Observe the data for 10 minutes. Comment on oscillation period and amplitude.*

(6) *Set the stiction band to d = 0. Comment on oscillation period and amplitude. Do the oscillations stop?*

(7) *Observe the output for 10 minutes.*

(8) *Set the stiction band to d = 4%. Observe the data for 10 minutes. Does the loop start oscillating again? What is the oscillation period and amplitude? Comment.*

STUDENT RESPONSE

In this section, we present a student report on the experiment. It can be seen from the report that the group had to think about the effect of various controller tuning concepts and also understand oscillations generated through nonlinearities.

Experimental Procedure

The liquid-level control experimental apparatus in Clarkson University's Undergraduate Laboratory was used for this experiment. A GUI developed using Simulink was used to adjust both the controller parameters and the simulated stiction. All relevant outputs and controller parameters

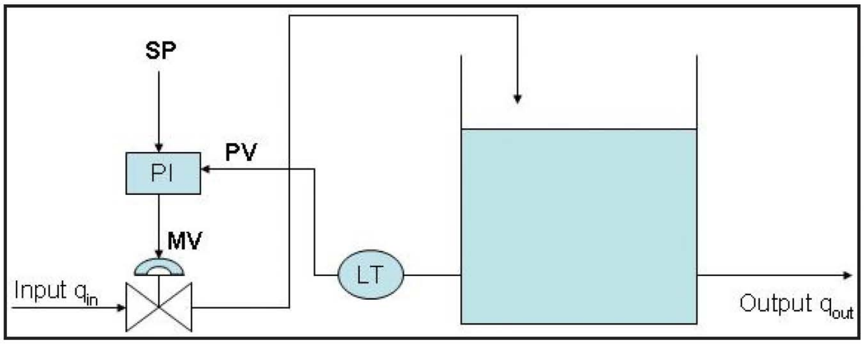

Figure 5*. Liquid-Level System.*

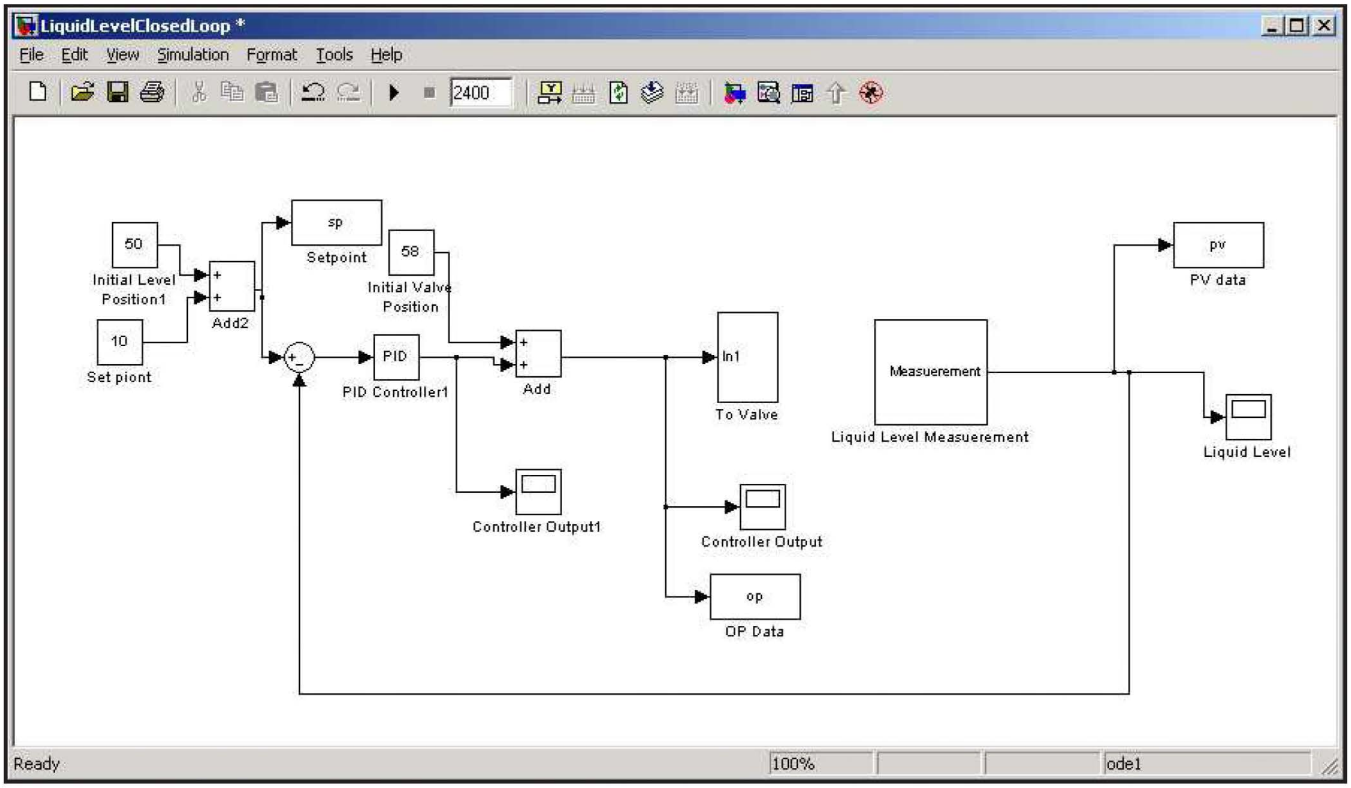

Figure 6*. Liquid-Level System controlled from Simulink.*

were recorded and plotted. First, the liquid-level set point was set to 40% and the process was run until steady state was achieved. Next, the level set point was decreased by a step of 10% and the stiction band was set to 4%. The oscillatory effect of the stiction band on the step response was observed. After about 15 minutes, the integral time constant of the controller was increased, and the oscillations in liquid-level were observed for about 7 minutes. The integral action was then reset to its original value and the controller gain was increased. After another observation period of about 7 minutes, the controller gain was reset to its original value. The stiction band was then set to 0, thereby eliminating the simulated stiction. The process was observed for about 5 minutes before the stiction band was set back to 4%. The effect of stiction reintroduction was observed for about 5 minutes.

Experimental Results

The experimental results were classified into six distinct regions. These are shown in Figures 7 and 8. Figure 7 shows the set point and the corresponding percent level vs. time. Figure 8 shows the controller output and the valve position percentages vs. time.

Region 1: Region 1 shows the start of the process. In this region, the percent level was relatively steady around the set point of 40%, as shown in Figure 7. The controller acted ideally and adequately compensates for process disturbances. As shown in Figure 8, the controller output and valve position signals were nearly identical, as the valve responded almost perfectly to the output of the controller.

Region 2: The transition between Region 1 and Region 2 occurred as simulated valve stiction was simultaneously introduced with a set point change to 30%. The effects of stiction are easily seen in Figure 8, where the valve position signal began to change in steps rather than closely following the controller output signal. The set point change also demonstrated the activity of the proportional element of the controller, such that as the step was made the output was proportionally adjusted. Shortly after the step change, the oscillatory effects of stiction, in conjunction with the effect of the integral action of the controller, were clearly observed. The further the level deviated from the set point, the more the controller output was adjusted by the integral action, until finally the 4% stiction band of the valve was overcome and the valve responded. Because of the stiction band, the valve response overcompensated, causing the level to increase or decrease. Again, the controller attempted to compensate for the error, resulting in the oscillatory behavior seen in both Figures 7 and 8. The large disturbance at around 750 seconds was a demonstration of a method used to combat stiction. This anomaly resulted in a "resetting" action for the controller, leading to a period of stable operation even though stiction was still a factor.

Region 3: Region 3 was characterized by a decreased period, and thus increased frequency, of oscillation, as seen in Figures 7 and 8. This was a response to an increase in the integral action of the controller, caus-

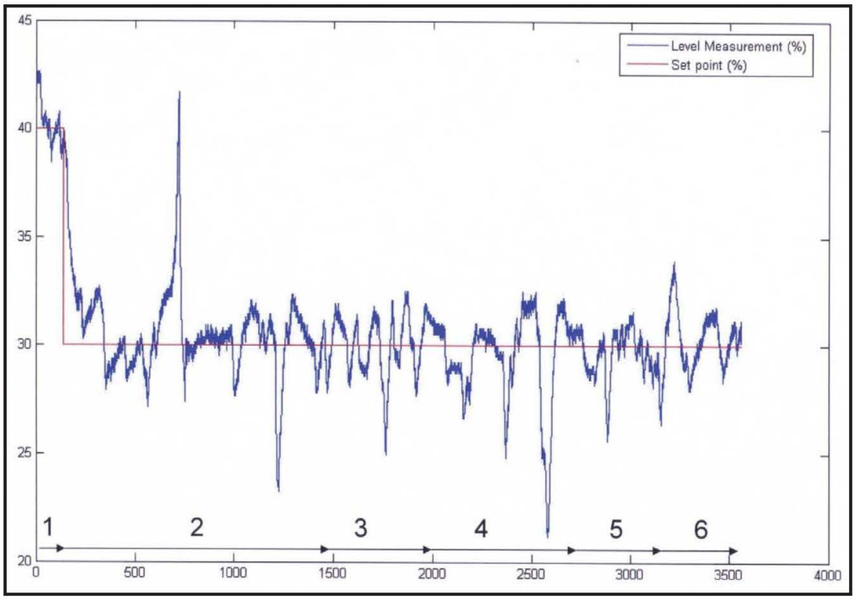

***Figure 7**. Set point and percent level.*

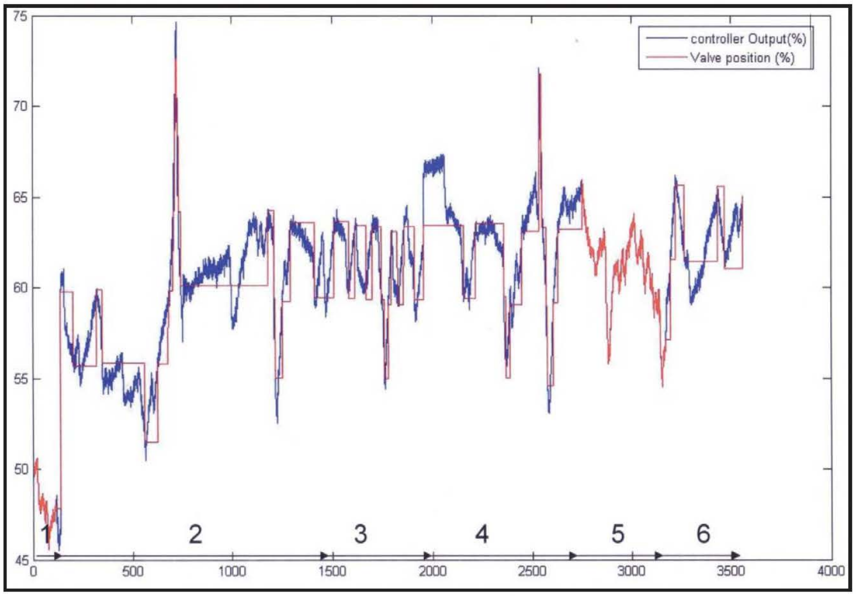

***Figure 8**. Controller output percent and valve position.*

ing the controller to respond more aggressively. With a more aggressive integral mode, the controller attempted to make corrections more quickly, resulting in the increased frequency of oscillation.

Region 4: In Region 4, the integral time constant was reset to its previous value and the controller gain was increased. This caused two distinct differences in the controller output, the valve position, and thus liquid level. By adjusting the controller's integral action back to the original setting, the period of oscillation returned to a value similar to that experienced in Region 2. By increasing the controller gain, the amplitude of the oscillations increased. This was demonstrated toward the end of this region as the liquid level began to quickly change through a wide range of values.

Region 5: Region 5 was characterized by the deactivation of the stiction band simulation and the controller gain being reset to its original value. Once these actions were taken, the valve once again responded ideally to the controller output, and the level returned to a more stable value. This behavior was similar to the behavior in Region 1.

Region 6: In Region 6, the stiction band simulation was again activated with a value of 4%, without changing any of the controller parameters. The oscillatory behavior of the process was observed with a frequency and amplitude similar to that experienced in Region 2.

CONCLUSIONS AND FUTURE WORK

When most control technologies are initially implemented in an industrial environment, they are well tuned and operate optimally. For a variety of reasons, however, it is usual for controller performance to degrade over time. Finding out which controllers are performing poorly, identifying the cause of poor performance, and suggesting corrective actions are the overall problems of CPA. Since it is the responsibility of control engineers to solve such problems on an almost daily basis, it is worthwhile to introduce CPA at an undergraduate level. In this article, a possible approach introducing undergraduate students to the concept of stiction in control valves is discussed. A student report on the lab experiment was also presented. There are several avenues for future work. Since the process control class does not have a lab component at Clarkson, it was difficult to teach stiction as a part of the curriculum. Only individual student groups could do this experiment as a project. To circumvent that problem, we are planning to make this experiment Web accessible.[33] This would make it possible for stiction to be taught in the classroom. Further, this would also make it possible for other universities to use the experiment in their classrooms.

Stiction phenomenon also introduces limit cycles, and it is possible to predict the limit cycle characteristics through, for example, describing function analysis. It was felt, however, that these concepts would be inappropriate for the undergraduate control class at Clarkson. As part of future work, we will try to introduce this experiment with limit cycle analysis as part of a graduate course in process control. Further, stiction is just one aspect of CPA. As discussed in the introduction, there is a need to teach CPA at an undergraduate level. With this goal, we are working on a three-tank setup that can be used as a lab experiment, to discuss the whole gamut of CPA problems.

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