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A Model Free Approach for Online Stiction Compensation

B.M. S. Arifin * C.J. Munaro **
M.A.A. Shoukat Choudhury *** S.L. Shah ****

* *Department of Chemical & Materials Engineering, University of Alberta, Edmonton, Alberta, Canada, T6G 2G6. (e-mail : arifin@ualberta.ca)*
** *Departamento de Engenharia Eltrica, UFES, Av Fernando Ferrari, 514, CEP 29075-910, Vitria, ES, Brazil. (e-mail : munaro@ele.ufes.br)*
*** *Department of Chemical Engineering, Bangladesh University of Engineering & Technology (BUET). (e-mail : shoukat@che.buet.ac.bd)*
**** *Department of Chemical & Materials Engineering, University of Alberta, Edmonton, Alberta, Canada, T6G 2G6. (e-mail : sirish.shah@ualberta.ca)*

Abstract: Stiction is one of the most adverse non-linearities that can affect a control valve. It impacts both valve longevity and product quality. Currently available stiction compensation methods either reduce the amplitude of oscillation at a cost of increased frequency or require knowledge about process and valve models. In this study a novel stiction compensation scheme is developed which reduces both oscillation amplitude and frequency, obtains good set point tracking and disturbance rejection, and yet requires minimal information about the process and is simple-to-implement online. The method has been successfully evaluated on a pilot plant interfaced to a commercial DCS system.

Keywords: valve-stiction, stiction-compensation, online compensation, DCS system, DeltaV.

1. INTRODUCTION

Constrained resources, stringent environmental regulations and tough competition between different industries have resulted in highly efficient manufacturing operations in terms of energy and raw material utilization, optimal quality products and safety of the plant personnel and surrounding communities all with a lower cost. Most of the modern plants are now automated to achieve these goals. Control loops are the essential part of these automated processes and in large process plants there are as many as hundreds and even thousands of such loops.

These control loops often suffer from poor performance due to process or actuator non-linearities, disturbances or poorly tuned or configured control strategies. Performance of over 26,000 PID controllers from a wide range of continuous process industries have been investigated [Desborough and Miller, 2002] and it is shown that the performance of over two thirds of installed loops (68% to be precise) was not satisfactory.

Other surveys [Srinivasan and Rengaswamy, 2005] in the past decade have also reported that only one third of industrial controllers provide acceptable performance. The presence of oscillations in a control loop results in loss of energy, increased product variability and hence reduction of profitability [Srinivasan and Rengaswamy, 2005]. Furthermore, 20 to 30% of all control loop oscillation problems are due to control valve stiction and other related valve problems. Stiction is termed as a hidden menace of control loops.

There are several methods [Choudhury et al., 2008a] for detection and quantification of stiction but only a few for stiction compensation. Stiction compensation methods help to minimize the effect of stiction up to the next process shut-down. Therefore methods for compensating stiction are of great importance to avoid unscheduled plant shut down. Among the available methods of compensation one of the most common methods is the knocker method [Hägglund, 2002]. It is one of the better methods in which a constant pulse is added to the controller signal to overcome stiction. But the pulse is characterized by three parameters and it causes the valve to move at all times which unfortunately can wear the valve out well before its designated life time. Various modifications of this method have been described in [Srinivasan and Rengaswamy, 2005], [Srinivasan and Rengaswamy, 2006]. The constant reinforcement (CR) [Xiang Ivan and Lakshminarayanan, 2009] method is similar to backlash compensation [Cuadros et al., 2012b] and is another improvement of the knocker method. In both cases the compensating signal is the varying controller signal with its sign multiplied by a constant. In the knocker method the compensating signal tries to overcome stiction and in the CR method it tries to overcome backlash.

In addition to these, the two move method [Srinivasan and Rengaswamy, 2008] is a recent approach for compensating stiction where the 1st move of the valve overcomes the stiction and second move brings the stem to its steady state position to reach the set point. The problem with this method is that it requires knowledge of the steady state position of the valve stem. Improvements to this method have been proposed in Cuadros et al. [2012a].

However none of the above methods can attain all the desired criteria of a stiction compensation method [Cuadros et al., 2012b] :
a) reduction of oscillations in process
b) reduction of valve movement,
c) no a-priori process knowledge requirement except for routinely available operating data.
d)good set point tracking and disturbance rejection and

Cuadros et al. [2012b] summarized the performance of the above methods as shown in Table 1 :

Table 1. Comparison of available Stiction Compensation Methods

Criteria	Knocker	CR	Two-Move
a	✓	✓	✓
b	×	×	✓
c	✓	✓	×
d	✓	✓	×

From Table 1 it is clear that the Knocker and the CR methods have all the criteria of a stiction compensation method except criteria b. On the other-hand the two move method has fulfilled criteria b but it does not fulfill criteria c at all. It is also vulnerable to disturbances and as a result it does not fulfill criteria d.

In this study a new method of stiction compensation has been developed which can attain all these characteristics in an online fashion.

2. COMPENSATION OF STICTION IN CONTROL VALVE

Since more than 90% of the industrial valves are pneumatic [Hägglund, 2002] and pneumatic valves exhibit slower dynamics than servo-systems, compensation techniques such as dithering and impulsive control [Armstrong-Hëlouvry et al., 1994] cannot be directly applied to process control loops [Srinivasan and Rengaswamy, 2005]. Hägglund [2002] and Kayihan and Doyle [2000] have addressed stiction compensation algorithms for pneumatic control valves. The approach of Kayihan and Doyle [2000] requires a valve model with valve parameters such as stem mass and stem length. The process model should also be known a-priori. Obtaining such detailed valve and model information for several hundred valves is a serious practical limitation [Hägglund, 2002].

To avoid these problems a new compensation technique for pneumatic valves called the knocker method was proposed [Hägglund, 2002], where short pulses of equal amplitude and duration in the direction of the rate of change of the control signal are added to the control signal (upper part of Figure 1). The sequence of pulses is given by

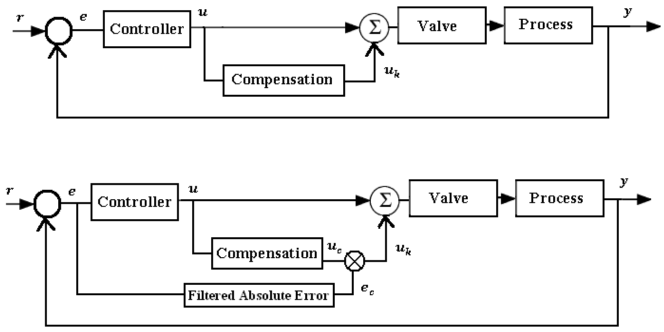

Fig. 1. Stiction compensation strategies.

$$u_k(t) = \begin{cases} a\ sign(u(t) - u(t_p)); & t \leq t_p + h_k + \tau \\ 0; & t > t_p + h_k + \tau \end{cases} \qquad (1)$$

where a is the pulse amplitude, τ is the pulse width, h_k is the time between each pulse and t_p is the time of onset of the previous pulse. Although it was assumed that there might not be significant wear on the valve due to the knocker technique, in a study [Srinivasan and Rengaswamy, 2005] about knocker performance it has been observed that there is significant valve movement with possibility of wearing the valve out when this algorithm was implemented on a pneumatic valve. In the same study, it was also found that the choice of knocker parameters influences its performance. An optimal choice of knocker parameters which can reduce valve movement as well as the oscillation was proposed by Srinivasan and Rengaswamy [2006], but this method requires perfect measurement of stiction parameters and the process model should be known a-priori.

In case of the CR method, the compensating signal u_k is calculated by the following equation

$$u_k(t) = a\ sign(\triangle u) \qquad (2)$$

where a is the estimated stiction. This method is found to decrease the variability in process variable (PV) at the expense of greater frequency of the valve stem oscillation, which again can cause severe wear of valve.

3. THE PROPOSED COMPENSATION METHOD

It is clear that both the knocker and the CR methods can reduce the detrimental effects of stiction, without any prior knowledge of the process and valve model, i.e., with minimal information. Also, they both can track the set point and reject disturbances. The problem with them is that in both cases the valve has to move a lot. In the case of CR, the valve moves more aggressively than the knocker method because of the higher amplitude of the pulses. On the other hand, characterizing the knocker signal requires three parameters to be chosen.

Hence, there is a clear need for a simple stiction compensation method that will not only reduce oscillations

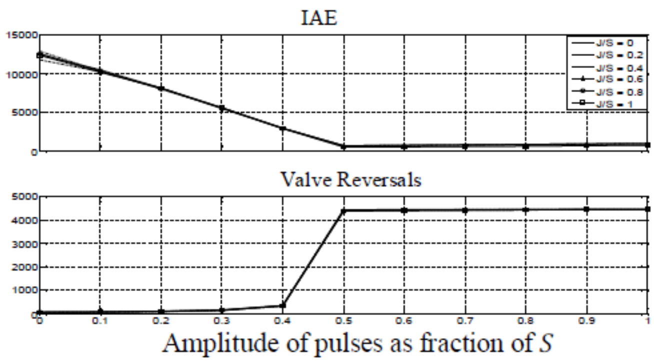

Fig. 2. Effect of the pulse amplitude as fraction of dead band plus stick band (S) on IAE and valve reversals.

due to stiction but will also avoid unnecessary valve movement, will track the set point and reject disturbances with minimal information about the process and which can be applied online. In the present study such a method has been developed which can be applied online to process plants.

To justify the proposal a process preceded by a sticky valve in closed loop is simulated with the CR compensation method with pulses of increasing amplitudes. In these simulations, a first order process with transfer function $G(s) = \frac{3}{100s+1}$ was used with stiction parameter $S = 4$ and parameter J was varied to get different $\frac{J}{S}$ ratios. The stiction model of Choudhury et al. [2005, 2008b] was used to simulate stiction, where S is the dead band plus stick band and J is the slip-jump. The amplitude of the pulses was changed for different $\frac{J}{S}$ relations, and the integral of absolute errors (IAE) and number of valve reversals (change of direction of valve movement) were measured. One can see that increasing the amplitude of the pulses reduces the IAE but increases the number of valve reversals (Figure 2). The trade-off between minimum IAE and valve reversals can be handled by changing the amplitude of the pulses accordingly. If the compensating signal is a function of the error, then as the error reduces so does the amplitude of the compensating signal; therefore a small error produces little or no valve movement. The proposed scheme is shown in the bottom panel of Figure 1.

The signal $u_c(t)$ is calculated using the knocker or CR methods. The amplitude of the pulses is $a = \frac{S}{2}$ in order to overcome stiction. The signal $e_c(t)$ is the filtered absolute error multiplied by a constant γ, which is between 0 and 1. The compensating signal is the product of e_c and u_c,

$$u_k(t) = e_c(t)u_c(t) \tag{3}$$

We now present some important considerations to ensure that this simple method works. The design requires only the measurements of the error and controller signals (e and u). From these signals, we obtain A_{OP}, the amplitude of u, A_E and w_o, the amplitude and frequency of oscillation of the error signal, respectively. These measurements are made under the assumption that the signals are oscillating due to stiction. The filter applied to the absolute error has a band-width related to the frequency of oscillation

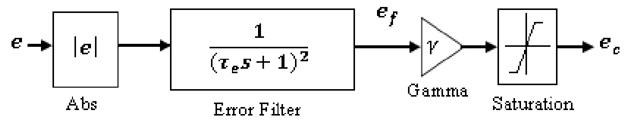

Fig. 3. Signal flow path for computation of the error signal.

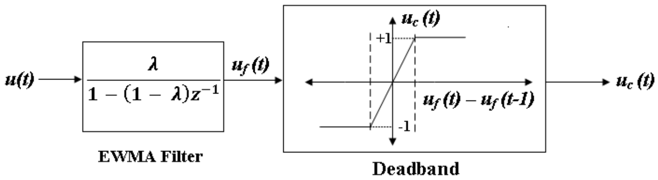

Fig. 4. Signal flow path for computation of the control signal u_c.

of u. The filter consists of two first order filters to make its implementation simple on commercial DCS. The time constant (τ_e) of this filter was chosen $\tau_e \geq \frac{1}{w_o}$, with greater values for noisy signals,to ensure that the oscillations are not attenuated. The value of γ is chosen in order to satisfy

$$A_E\gamma \geq A_{OP} \tag{4}$$

A_E is calculated using u and the attenuation provided by the designed filter using w_o. The error signal is measured during the limit cycles. This value of γ assures that the pulses have an amplitude large enough to overcome stiction. Since disturbances and changes in the set point can produce larger variations in the error signal, a saturation is applied to e_c, so that its limits are within the interval $[0, 1]$. The filtering and calculations on the error signal e are illustrated in Figure 3. e_c is the error from which the compensation signal u_k is calculated and added to the controller output u.

The EWMA (Exponentially Weighted Moving Average) filter applied to u has the important objective of ensuring that the pulses are applied properly. Since this signal tends to be noisy, the direction calculated using its derivative can be affected, producing pulses in wrong direction that increase the time for the compensation to eliminate the oscillation. An EWMA [Seborg and Mellichamp, 2006] filter was used for u, since its implementation is quite simple on DCS and just one parameter is required for tuning according to the level of noise. An additional dead band block is also applied before calculating $sign(\triangle u)$, to ensure that very small variations on u do not produce unnecessary pulses. Its value will be defined by δ_u. The calculation steps to produce u_c from u are illustrated in Figure 4.

Finally, a dead band for PID control is also used. This strategy is usual in industry when the integral action should be disabled for small errors. In our case, since a small error persists after compensation, causing the integral action to act and to bring the oscillation back, a small dead band based on limits on the error amplitude is used. We emphasize that this is a built in parameter

Fig. 5. Pilot plant for performing the experiments.

in the PID blocks of almost all DCSs. This dead band will be described by δ_{PID}. We can now describe the steps required for the design of the proposed stiction compensation scheme:

1. Collect u and $e(= r - y)$ during some periods of oscillation and obtain A_{OP}, A_E and w_o.
2. Calculate $\gamma \geq \frac{A_{OP}}{A_E}$ (as per equation 4).
3. Calculate time constant for error filter, $\tau_e \geq \frac{1}{w_o}$ [unit $= \frac{sec}{rad}$].
4. Select λ in the EWMA filter to reduce noise. Values around 0.5 are a good choice in general. It depends upon how noisy the controller output signal u is.
5. Calculate dead band for u_c, $\delta_u \leq 0.1A_{OP}$.
6. Calculate dead band for PID controller, δ_{PID}, based on maximum error. A reasonable choice is $\delta_{PID} > 0.2\, max(e)$ (maximum after applying compensation).

4. EXPERIMENTAL VALIDATION

To validate the proposed stiction compensation method some experiments were performed on a level loop of a computer interfaced pilot plant in the computer process control laboratory at the University of Alberta (Figure 5). The pilot plant is equipped with a Delta V DCS system.

4.1 Experiments with the Existing CR Method on a Level Loop

Figure 6 shows the experimental evaluation of the constant reinforcement (CR) scheme for compensation of stiction. From this figure, it is clear that the CR method could eliminate the high amplitude low frequency oscillations at the expense of small amplitude high frequency oscillations and aggressive valve movements. The knocker method also shows similar results but it is less aggressive than the CR method in terms of the valve movement.

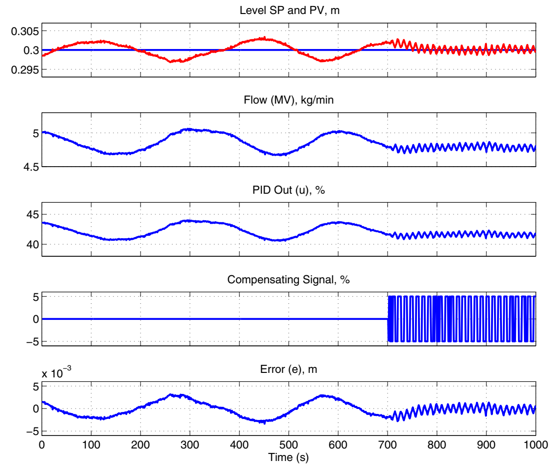

Fig. 6. Experimental evaluation of CR compensation scheme. The scheme reduces the amplitude of oscillation but increases limit cycle frequency.

4.2 Experiments with the Proposed Method on a Level Loop

The proposed compensation scheme was applied to the same level loop (as shown in Figure 5). In this case the proportional gain was 2 and reset time (integral action time constant) was 50s for the PI controller. The scan rate of the level measurement in the Delta V system was selected to be 1s. The result is shown in Figure 7. Here, for the first 786 seconds no compensation scheme was active; there after the proposed compensation scheme was initiated. In this case $A_{OP} = 2.79$, $A_E = 0.003$ and $w_o = \frac{2\pi}{267}\frac{rad}{s}$. The parameters for the proposed scheme were calculated as $\tau_e = \frac{1}{w_o} = 42$, $\gamma = 930$, $\lambda = 0.6$, $\delta_{PID} = 0.001$ and $\delta_u = 0.25$. It is clear that the proposed scheme was able to break the oscillation due to stiction. To check the effect of the noise, the valve was set to manual mode at 1692s and it is clear that there exist some measurement noise and that the valve was not moving.

4.3 Experiments with the Proposed Method on a Flow Loop

The scheme was applied to control the inlet flow rate of the same tank shown in Figure 5 to show the applicability of the method for fast process dynamics. Since the flow loop is faster, in this case the Delta-V block scan rate was selected to be 0.1s. This was to make sure that there is enough time for calculation before the valve changes its direction and the compensating signal was applied at the right moment. In this case the proportional gain was 1 and reset time was 0.6s for the PI controller. In the tests for the level loop the flow was around 5 kg/min, while in the tests for flow loop it was around 2 kg/min. The signature obtained for the valve showed that stiction changes considerably for different points of operation, changing the amplitude of the controller signal (Figure 8).

Figures 9 and 10 represent some of the results from these experiments. In Figure 9, over the first 169 seconds, there was no compensation; from 170 seconds onwards the CR

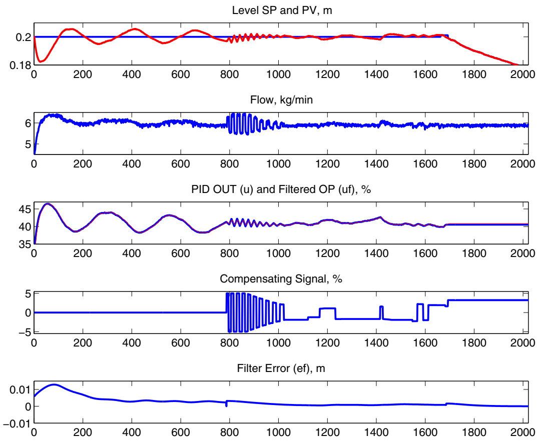

Fig. 7. Experimental Result for the level loop. There was a sustained oscillation in the process up to 786s. Then the proposed scheme was activated at 787s. The proposed scheme was able to arrest the effect of stiction. At 1692s the process was set to manual mode to show the presence of measurement noise.

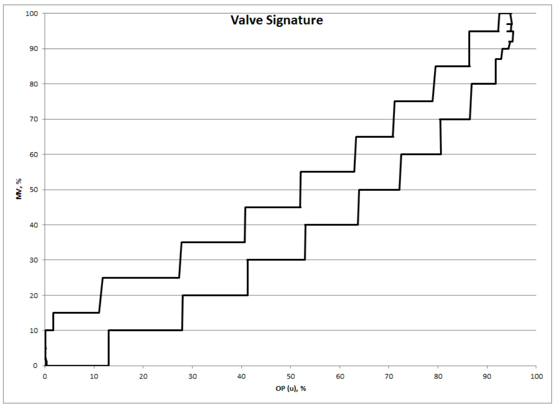

Fig. 8. Signature of the sticky control valve (MV vs. OP plot).

compensation scheme was applied. Using data from the first 169s, the following values were obtained: $A_{OP} = 15.92$, $A_E = 0.68$ and $w_o = \frac{2\pi}{7}\frac{rad}{s}$. Using these values and the expressions in the six steps of the compensation scheme, one obtains: with $\tau_e = 1.1$s, $\gamma = 22.9$, $\lambda = 0.6$, $\delta_{PID} = 0.1$ and $\delta_u = 0$. The value of τ_e was 5 to further reduce noise effects. From 513 seconds onwards, the proposed compensation scheme was active. From 689s onwards, a set point change was implemented with the proposed compensation scheme at work. The figure does show that the proposed scheme works well also during a step change. Figure 10 is the zoomed-in version (from 350s to 650s) of Figure 9 to clearly show the difference between CR and the proposed case. After the proposed scheme was activated, the valve movement reduced significantly.

Figure 11 shows the effect of set point change while the proposed scheme was at work. At 18s the set-point was changed from 2 kg/min to 5 kg/min with the proposed scheme being active. This figure shows that the proposed compensation scheme also works well when a new distur-

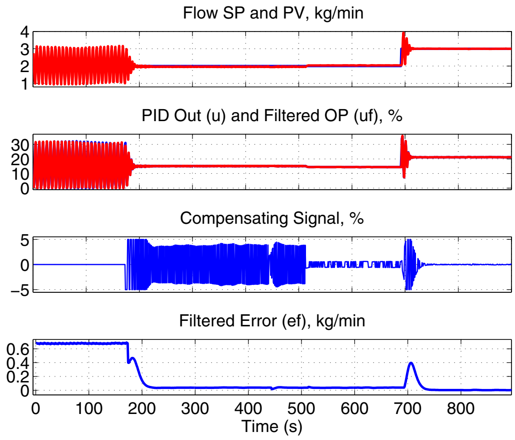

Fig. 9. Effect of CR (170 to 512s) and the proposed compensation (513s onwards) on the flow loop. It shows that in the case of CR scheme the compensating signal is higher and hence the valve movement is also higher.

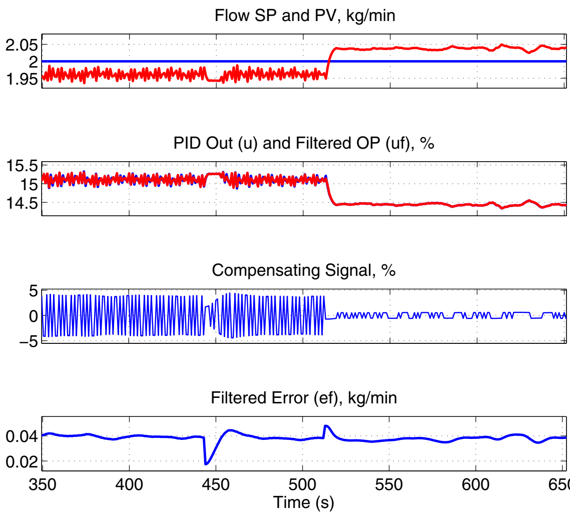

Fig. 10. Zoomed-in Version of Figure 9. Notice that the valve movement is significantly reduced with the proposed scheme.

bance affects the system. It is to be noted that at 297s, a disturbance affected the set point. The proposed scheme handled the disturbance quite effectively.

From Figures 7, 9 and 11 it is clear that the filtered error provides a good compensation mechanism to change the amplitude of the pulses to handle stiction and to have the PV converge in the vicinity of the SP. Though initially the valve moved a lot, but as the PV neared the SP, the valve movement stopped and the valve there after only moved when a new error was introduced. Figure 12 is a zoomed in version of Figure 11. It shows that the proposed scheme handled the disturbance quite effectively and at 392s the effect of disturbance was minimized. At 493 s, the valve was set to manual mode to show that small variations

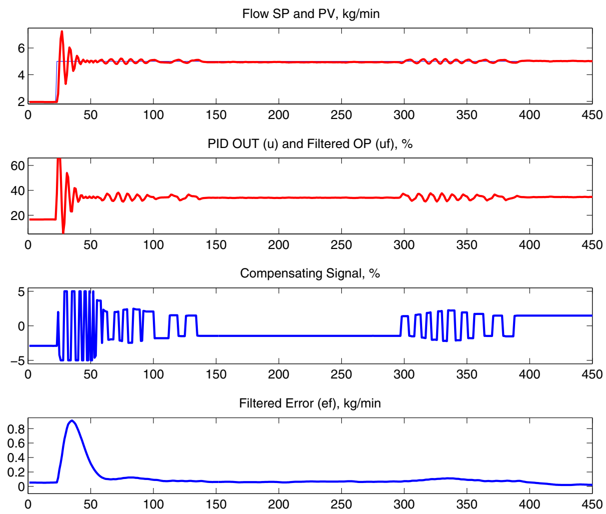

Fig. 11. Set-point tracking (18s) and disturbance rejection (297s) properties of the proposed compensation strategy. The compensating signal is added when there is an error. But when the error reduces, the compensating signal is automatically reduced.

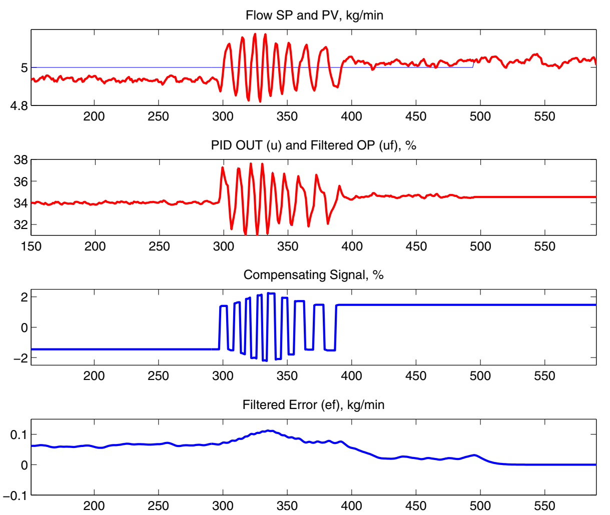

Fig. 12. Zoomed-in version of Figure 11. At 297s, a disturbance was introduced and the compensation scheme tackled this disturbance and took the process to the desired condition at 392s. The process was set to manual mode at 493s to show the presence of measurement noise.

on flow come from noisy measurements, not from valve movement.

5. CONCLUSIONS

This paper describes a novel method for compensating valve stiction. The main contributions can be summarized as :

1) A novel valve stiction compensation technique has been developed which can not only eliminate oscillations without aggressive control actions but also can achieve good set-point tracking and disturbance rejection.
2) The proposed method neither requires a process model nor any input from the operators.
3) The method is applicable to both fast and slow control loops such as flow and level loops.
4) The method has been successfully implemented on a pilot-scale laboratory tank system which was interfaced using a commercial Delta-V DCS system.

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