ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, RibeirãoPreto, SP, Brazil

STICTION COMPENSATION METHOD BASED ON MAPPED CONTROL FOR VALVE STEM POSITION

Matheus Cammarosano Hidalgo
Claudio Garcia
Escola Politécnica da USP, Av. Prof. Luciano Gualberto, Travessa 3, nº 380, Butantã São Paulo, 05508-010
matheus.hidalgo@usp.br
clgarcia@lac.usp.br

Abstract. *Friction in control valves is one of the main sources of variability in control loops. There are several stiction static friction) compensation methods that attempt to reduce the variability, most of them are meant to be used with the PID controller.These algorithms can reduce the variability, but the valve stem still oscillates around the set-point value indefinitely, which is something undesirable, since the consequence of this fact is an increased wear of a valve that already has problems. This paper introduces a stiction compensation method that controls the valve stem position with an algorithm that is not just based on the PID controller, but in an input-output mapping instead, the offset control method.This new method has the objective of reducing the variability without making the valve stem oscillating around the set-point.The experiments were performed with two different control valves, one with low and the other with high friction. Two methods were tested: one of them is the new one and the other is a traditional friction compensation method based on the PID controller. For both algorithms, the internal absolute error and the number of reversions were evaluated and the results were quite good.*

Keywords:*Control valves; Friction compensation; Control loop performance.*

1. INTRODUCTION

Control valves are the final elements of most of the industrial control loops. Around 20% to 30% of the loop variability cases in control loops are caused by friction or hysteresis in the valve (Srinivasan and Rengaswamy, 2005). If the stiction (static friction) of the valve is considered too high, there are two ways to solve the problem: when it is possible, to stop the process and to submit the valve to maintenance (Hidalgo and Garcia, 2012). But the most common situation is when the process cannot be stopped and so it might be desirable to activate a compensation algorithm to allow the loop to operate with a high friction valve. In this paper, it will be introduced a stiction compensation method under two different conditions and the results will be compared with another compensation method.

In the next sesction, there is a brief discussion of the stiction model used to elaborate the algorithm. In Section 3, the description and the fundamentals of the algorithm introduced. Section 4 describes the experiments performed and in Section 5 the results are discussed. The last section is dedicated to the conclusions.

2. STICTION MODEL

There are several models that can describe thebehavior of control valves with friction (Garcia, 2008). They can be divided into two types: static, which define the friction as a static function of the stem speed and dynamic, whose parameters vary with the time (Garcia, 2006).

In Fig. 1 is shown a scheme of a globe valve with its respective parts, where the friction occurs in the gasket.

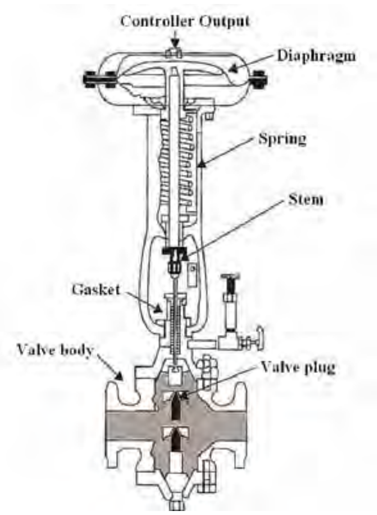

Figure 1. Globe valve and its respective parts

In this paper it is used the model of Kano (Kano et al., 2004), that describes friction using two parameters (Hidalgo and Garcia, 2012), the first one is called *S*, which is the variation of the control signal necessary to move the valve stem when there is a change in themovement direction. This parameter can be described by this Eq. (1):

$$S=F_s+F_d \tag{1}$$

Where F_s is the static friction force and F_d is the dynamic friction force, both given in pu (per unit) or percentage. The other parameter of the valve is the J (slip jump), which is the variation of the control signal necessary to move the valve stem when it stops and is required to start moving in the same movement direction. It is given by (Hidalgo and Garcia, 2012):

$$J = F_s-F_d \tag{2}$$

The effect of these two parameters can be noted on Fig. 2, which is a typical signature curve of a valve with some considerable friction.

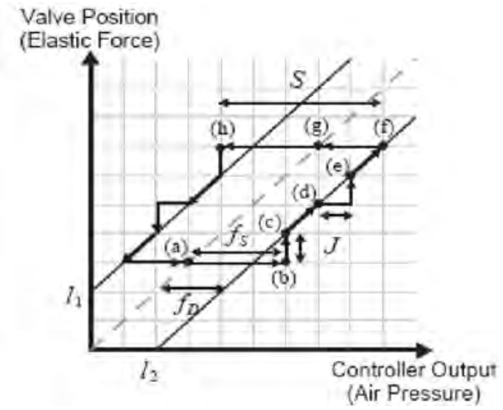

Figure 2. Typical signature curve of a valve with considerable friction (Kano, 2004)

3. OFFSET CONTROL METHOD

In practice, analyzing Fig. 2, the control effort necessary to change the direction of movement of the valve stem position is not the same in the two directions.

Furthermore, if you do not consider the slip jump between the points c and f, you can consider that the relation between the input and the output is linear on this part of the curve. In Fig. 2 it is shown a valve position x controller output graphic, but instead, it is possible to plot the inverse relation between these two variables, which is shown on Fig. 3.

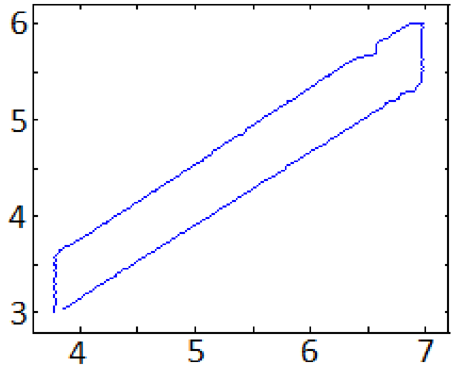

Figure 3. Controller output x valve stem position

With this graphic, it is possible to take the two regions where the valve stem position varies and use the least square method to interpolate the equation of two lines. Affirming that u is the controller output (or control signal), x and x_{ref} are the current position and the desired position, respectively, it can be said that:

$$u = u(x,x_{ref}) = k_1x_{ref}+k_2,\ if\ x_{ref}-x > 0 \tag{3}$$

$$u = u(x,x_{ref}) = k_3x_{ref}+k_4,\ if\ x_{ref}-x < 0 \tag{4}$$

The Eq. (3) and Eq.(4) are not sufficient as a control law, because they do not consider the imprecision of the approximations that were used and neither the effects of the slip jump or possible disturbances in the process.

So it is necessary to include a new term in Eq. (3) and Eq.(4) in order to correct these issues:

$$u = u(x,x_{ref}) = k_1x_{ref}+k_2+k_1x_{off}(x,x_{ref},t),\ if\ x_{ref}-x > 0 \tag{5}$$

$$u = u(x,x_{ref}) = k_3x_{ref}+k_4+k_3x_{off}(x,x_{ref},t),\ if\ x_{ref}-x < 0 \tag{6}$$

Where x_{off} is the correction term. It is important to see that this term corrects the linear coefficient of the line. So, this algorithm is most indicated to be used in processes with additive disturbances.

Before describing the equations that generate the offset term, it is necessary to note that in a control loop there are two kinds of operation modes: servo and regulation mode. The first one typically is the set-point tracking and the second is a disturbance rejection mode. It is important to say that the correction term is not to drive the process variable to the set-point, it is to make adjustments in order to correct errors.

This way, it was created two variations of the method, whose difference is the equation of the offset term. These equations are show next.

3.1 Offset term without deadband

The equations for this term are:

$$x_{off}(x,x_{ref},t) = x_{off}(x,x_{ref},t-1),\ if\ t-t_{changed}<0.9t_r \tag{7}$$

The algorithm is implemented in discrete-time, so Eq.(7) describes that if the current time (t) minus the moment when the se-point changes ($t_{changed}$) is less than 90% of the rising time (t_r) of the process, the current offset is equal to the previous.

$$x_{off}(x,x_{ref},t) = x_{off}(x,x_{ref},t^*) + K_p[(x_{ref}-x) + 1/T_i\int_{t^*}^{t} x_{ref} - x dt],\ otherwise \tag{8}$$

If the conditions of Eq.(7) are not satisfied, Eq.(8) determines the current value of the offset. It is clear that the correction of the error is made by a PI controller. The term t^* corresponds to the instant that the $t^*-t_{changed}=0.9t_r$.

3.2 Offset term with deadband

In this case, the equations for the offset are:

$$x_{off}(x,x_{ref},t) = x_{off}(x,x_{ref},t-1),\ \text{if } t-t_{changed}<0.9t_r \text{ or } |x-x_{ref}|<Tol \qquad (9)$$

Where Tol is an error tolerance that depends on the process, noise and other parameters. In other words, the difference between the two cases is a deadband that tolerates small values of errors. Otherwise, Eq.(8) describes the behavior of x_{off} in this case.

4. EXPERIMENTS PERFORMED

The experiments were carried out with two different control valves, one with graphite gasket and a high stiction value and the other with Teflon gasket and a low friction rate. The process variable of the control loop was the valve stem position. For both valves, the controller output is a 4-20 mA signal that is converted to pressure by an I/P converter. The valves are shown on the figures below.

Figure 4. Graphite gasket valve

Figure 5. Teflon gasket valve

Furthermore, the tests were performed with the two variants of the algorithm described in Section 3 and another stiction compensation method was tested, the knocker pulses method, which is based on a combination of a PID controller and repetitive pulses that attempt to reduce variability (Hägglund, 2002).

Moreover, it was performed three tests with each algorithm, one of them to evaluate the performance on steady-state, which will be measured the internal absolute error (IAE), which is given by:

$$\text{IAE} = 1/(T_2-T_1)\int_{T_1}^{T_2} |e(t)|dt \qquad (10)$$

Where $e(t)$ is the error. And the valve reversion index (VR) is given by (Cuadros, 2011):

$$VR(t) = 0, \text{ for } t = 1 \qquad (11)$$

$$VR(t) = VR(t-1)+1, \text{ if } W(t)\neq W(t-1) \qquad (12)$$

$VR(t) = VR(t-1)$, *otherwise* (13)

Where W(t) is described by:

$W(t) = sign(x_f(t)-x_f(t-1))$ (14)

Where x_f is the filtered process variable. The second test is a step response due to set-point change, in other words, is a servo mode test, where will be measured the rise time, the maximum overshoot and settling time.

The last test is a disturbance rejection test, where will be set two additive disturbances. The structure of the control loop is given on Fig. 6.

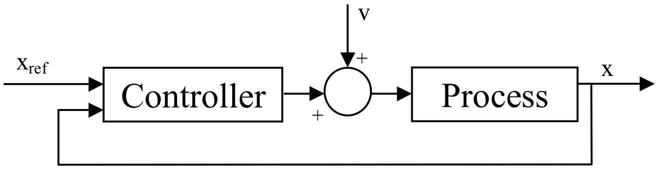

Figure 6. Block diagram of the control loop

In Fig. 4, v is a disturbance signal that can be inserted.

For each method, is used a different control tuning for the PI controller, which is shown on Tab. 1 and Tab. 2.

Table 1. Control tuning for each method for the graphite gasket valve

	K_p	T_i (s/repeat)
Knocker	1.0	1.8
Offset control without deadband	0.01	0.05
Offset control with deadband	0.005	0.0033

Table 2. Control tuning for each method for the Teflon gasket valve

	K_p	T_i (s/repeat)
Knocker	1.0	1.8
Offset control without deadband	0.0005	0.05
Offset control with deadband	0.03	0.0167

5. RESULTS

5.1 Steady State Experiment

This experiment consisted in a 1950 s test with the set-point in a determined value and no disturbances on the control loop.

5.1.1 Graphite gasket valve

In Fig. 4 there is the steady state response of the method of knocker pulses and the offset control without deadband.

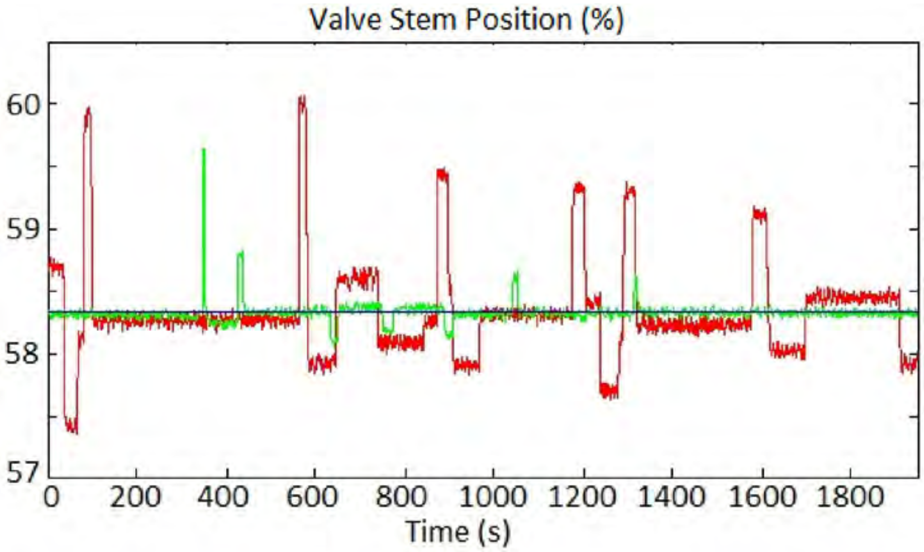

Figure 7. Knocker method response (red), offset control without deadband (green) response and set-point (blue) for the graphite gasket valve

And in Fig. 8 is shown the response of the offset control with deadband and the method of knocker pulses.

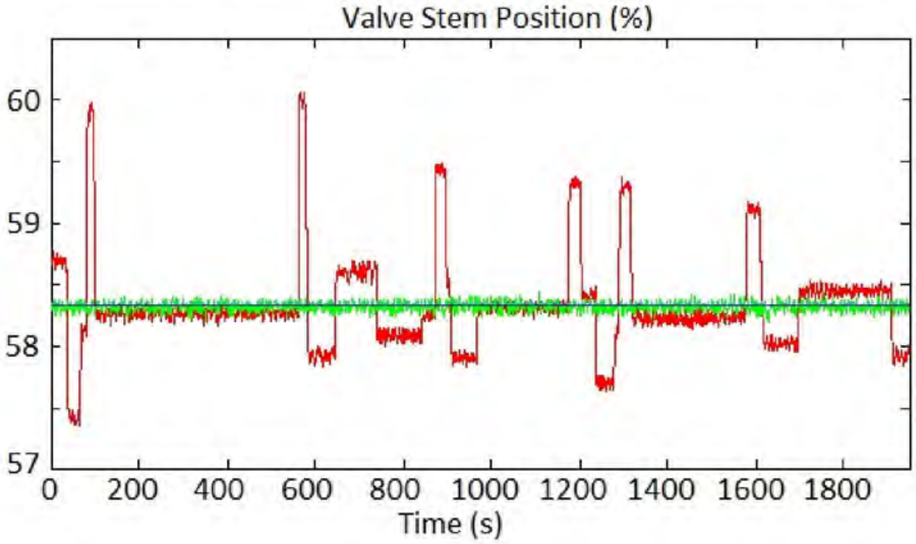

Figure 8. Knocker method (red) response, offset control with deadband (green) response and set-point (blue) for the graphite gasket valve

And the results of the indexes mentioned on Section 4 are:

Table 3. IAE and VR for the graphite gasket valve

	IAE	VR
Knocker	0.2358	15
Offset Control Without Deadband	0.0361	12
Offset Control With Deadband	0.0280	5

The IAE of the offset control method with deadband was the lowest one, followed by the same method without deadband and the knocker pulses method with the biggest one, around 8 times bigger than the lowest one.

ISSN 2176-5480

Furthermore, the number of reversion (VR) of the offset control with deadband was the lowest due to the deadband, which does not permit the PI controller to change the offset term. But even with the filtering is hard to evaluate this index, because the variations of the valve stem position are too small and there is some noise to interfere with the measuring. Consequently, the filtering reduces the noise, but it does not vanquish. The other two cases presented similar number of reversions, with the offset control with a little bit less quantity.

5.1.2 Teflon gasket valve

The Fig. 9 compares the results of the knocker pulses method and the offset control without deadband:

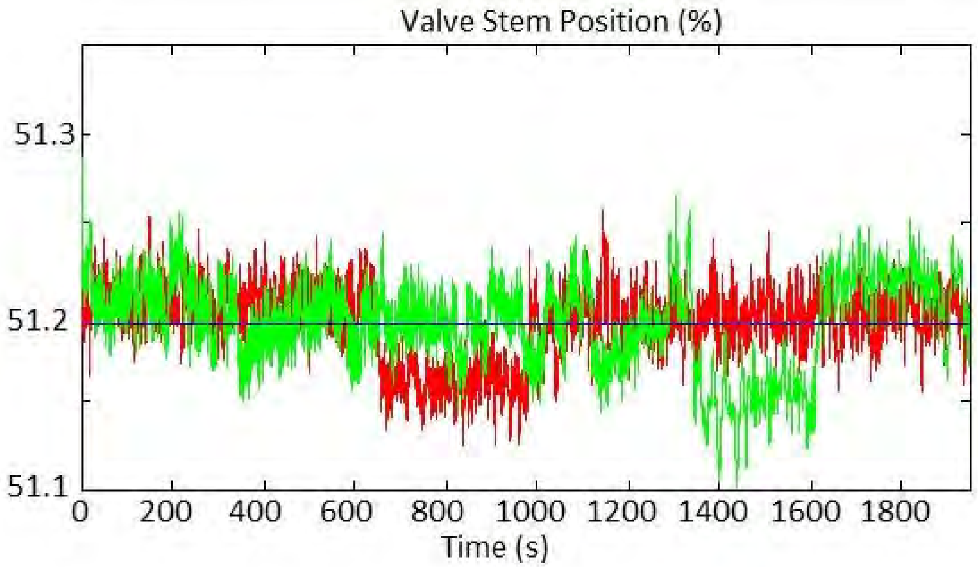

Figure 9. Knocker method (red), offset control without deadband (green) responses and set-point (blue) for the Teflon gasket valve

Now comparing the knocker method and the offset control with deadband.

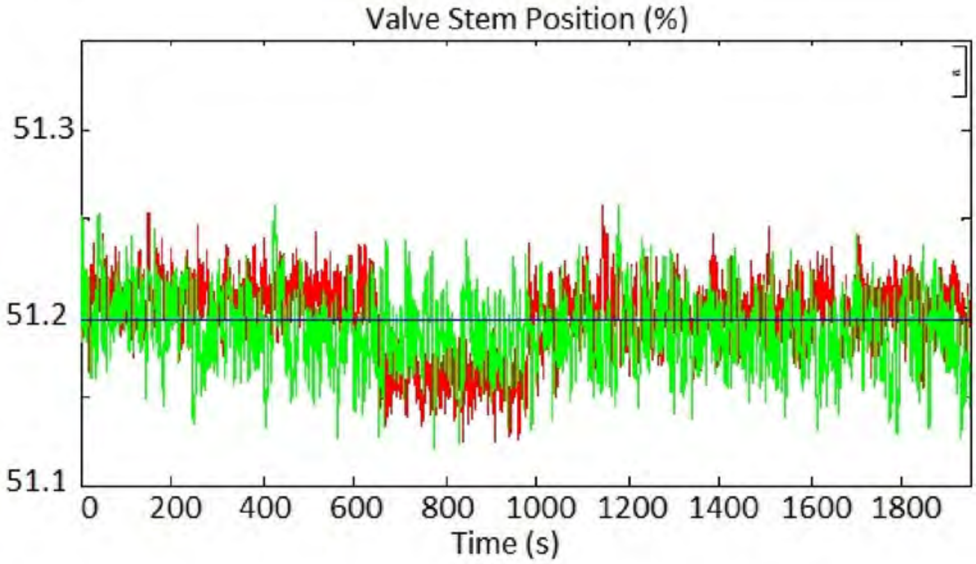

Figure 10. Knocker method response (red) and offset control with deadband response (green) and set-point (blue) for the Teflon gasket valve

And the performance indexes are pointed on Tab. 4:

Table 4.IAE and VR for the Teflon gasket valve

	IAE	VR
Knocker	0.0148	1
Offset Control Without Deadband	0.0187	7
Offset Control With Deadband	0.0137	0

The IAE for the offset control with deadband was the lowest one, followed from the knocker method with a close value and the offset control without deadband with the highest value.

The VR analysis was not something easy to evaluate, because even with the filtering, there was some noise, which affects the counting. So, analyzing the graphics, it was estimated the values presented on Tab. 2. Even though, it is not a completely trustworthy value. But the results were somehow similar to the IAE, with the offset control with deadband presenting the best result, with the knocker with a close value and the offset control with deadband with the worst performance.

5.2 Servo Mode Experiment

In this experiment, it was inserted a step on the set-point, in order to evaluate the response of the control loop for the two valves.

5.1.3 Graphite gasket valve

The results are shown in Fig. 11.

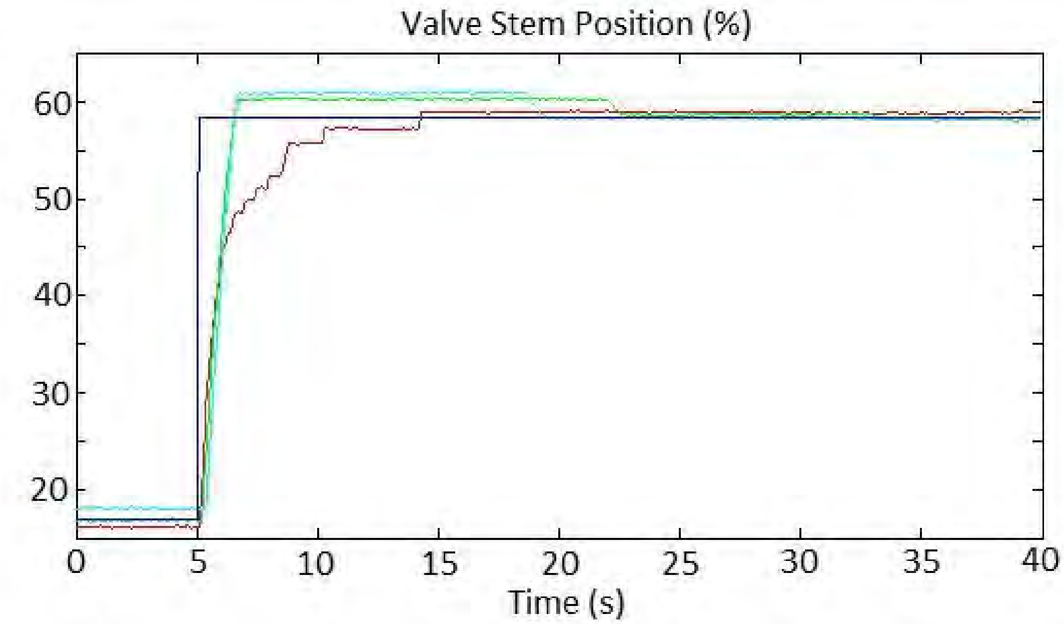

Figure 11. Step response of the three methods for the graphite gasket valve. Knocker method (red), offset control without deadband (green), offset control with deadband (cyan) and set-point (blue)

And the performances indexes are shown on Tab. 5.

Table 5. Rising time, maximum overshoot and settling time for the graphite gasket valve

	t_r(s)	M_p(%)	t_s(s)
Knocker	3.7	-	5.2
Offset Control Without Deadband	1.4	3.5	1.5
Offset Control With Deadband	1.4	4.7	1.5

ISSN 2176-5480

The rising time for the offset control method was much better than the knocker method, this happened because of the term that is proportional to the set-point and leads the system to a point closer to the reference quickly.

The knocker method had a slower response, but smoother and did not present overshoot. The two cases of the offset control presented a small overshoot.

For the settling time, it was used the 5% criteria and the offset control presented better results due to its quicker response to a set-point changing.

5.1.4 Teflon gasket valve

The step responses for this valve are shown below.

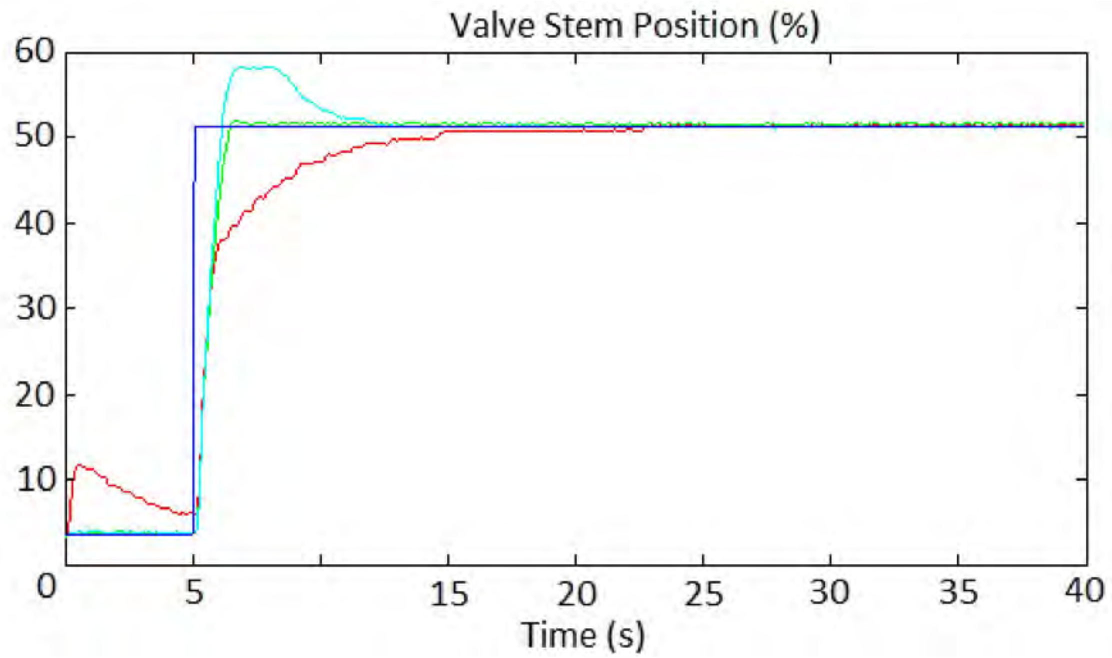

Figure 12. Step responses for the Teflon gasket valve. Knocker method (red), offset control without deadband (green), offset control with deadband (cyan) and set-point (blue)

Table 6. Rising time, maximum overshoot and settling time for the Teflon gasket valve

	$t_r(s)$	$M_p(\%)$	$t_s(s)$
Knocker	4.2	-	6.6
Offset Control Without Deadband	1.2	1.6	1.3
Offset Control With Deadband	1.0	13.7	4.8

The rising time of the offset control method is smaller than the knocker method. By the other side, the deadband permits a more aggressive tuning without oscillations, so the offset control with deadband presented ahigh overshoot comparing with the other cases.

The knocker method presented a slower but smoother response.

5.3 Regulation mode experiment

In this case, it was inserted a negative step on t=5 s and a positive step with t=55 s.

5.1.5 Graphite gasket valve

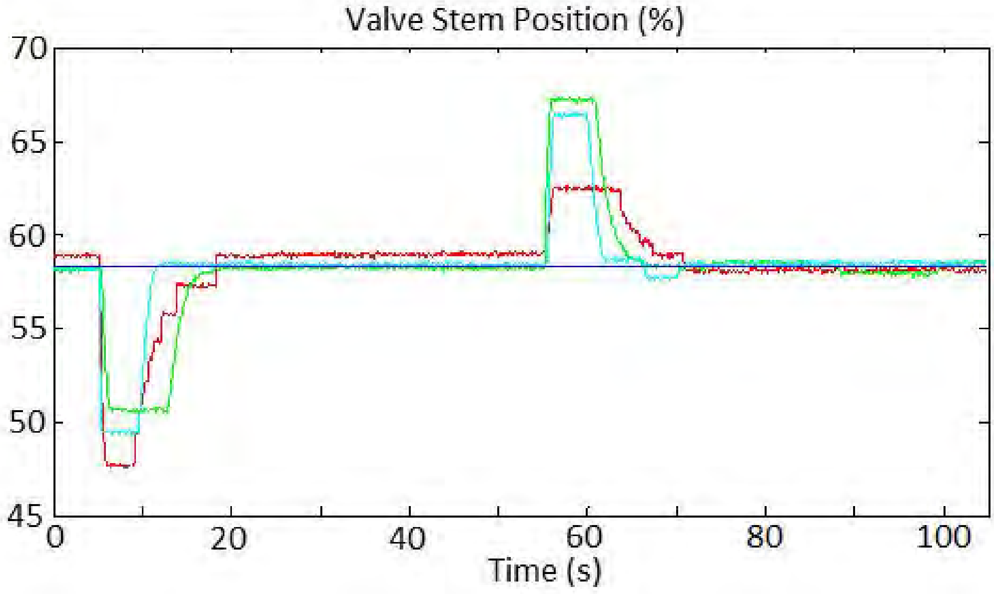

Figure 13. Regulation mode for graphite gasket valve. Knocker method (red), offset control without deadband (green), offset control with deadband (cyan) and set-point (blue)

The offset control with deadband presented the quickest disturbance rejection, followed by the offset control without deadband and the knocker method with the slowest one. The reason for these results are that the chosen tunings for the offset control method have a very small proportional gain, so it cannot avoid the deviation initially, but a higher integral gain, that allows a faster return to the set-point. With the deadband it is possible to use more aggressive tunings, because it does not permit that the PV oscillates around the set-point.

5.1.6 Teflon gasket valve

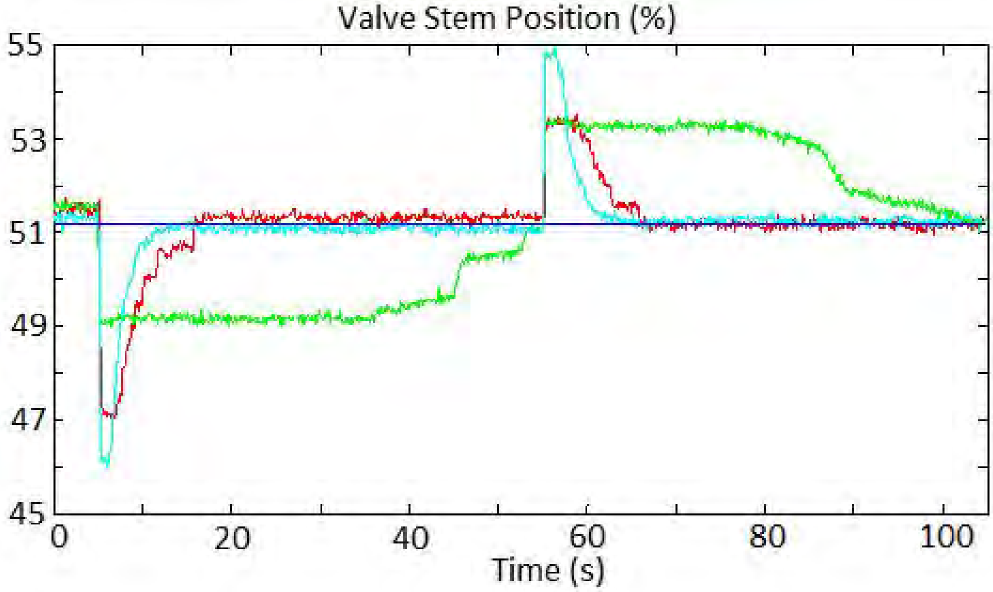

Figure 14. Regulation mode for the Teflon gasket valve. Knocker method (red), offset control without deadband (green), offset control with deadband (cyan) and set-point (blue)

The offset control with deadband initially did not avoid the disturbance well, but it was the first to correct it completely. This is due to the control tuning, with a smooth proportional gain and an aggressive integral gain. The offset control without deadband presented the slowest response to completely reject the disturbance, but it was the one which rejected it better at first. The knocker pulses method presented equilibrium between the initial and the complete disturbance rejection.

6. CONCLUSIONS

The offset control method is a new way to attack the problem of friction o control valves. In this algorithm, the PI controller has the function of correcting increments of the process variable or model imprecisions instead of driving the process to the set-point in any situation. This permit to obtain good results with different kinds of control tunings, with very small proportional gains and very aggressive integral gains at the same time, almost like an integrator and without inserting oscillations on the system. This kind of tuning in a control system with a PI controller only would produce terrible results.

Furthermore, the method presented excellent results comparing with the knocker method for the graphite gasket valve, with a very high stiction index. For the Teflon gasket valve, the results in steady state were similar comparing with the knocker pulses algorithm, with some points with a better performance and other with a worse. One reason for that it was the fact that it was not found a control tuning that produced equilibrium between a good transient response and a small IAE on steady state.

Finally, the next step of the research is testing this method for others control loops, with different kinds of dynamics in order to make it more robust and reliable.

The offset control method is a new way to attack the problem of friction in control valves. In this algorithm, the PI controller has the function of correcting increments of the process variable or model imprecision instead of driving the process to the set-point in any situation. This allow to obtain good results with different kinds of control tunings, with very small proportional gains and very aggressive integral gains at the same time, almost like an integrator and without inserting oscillations in the system. This kind of tuning in a control system with a PI controller only would produce terrible results.

Furthermore, the method presented excellent results comparing with the knocker method for the graphite gasket valve, with a very high stiction index. For the Teflon gasket valve, the results in steady state were similar comparing with the knocker algorithm, with some points with abetter performance and others with a worse. One reason for that it was the fact that it was not found a control tuning that produced equilibrium between a good transient response and a small IAE in steady state.

Finally, the next step of the research is to test this method for others control loops, with different kinds of dynamics in order to make it more robust and reliable.

7. ACKNOWLEDGEMENTS

I would like to thank Bruno Silva, who shared the knocker method algorithm that he implemented for his research.

8. REFERENCES

Cuadros, M.A.S.L., 2011. “Friction quantification and compensation on pneumatic control valves”.PhD thesis. Universidade Federal do Espírito Santo (in Portuguese).

Garcia, C., 2006. “Friction Modelling in Control Valves”.XVI Brazilian Congress of Automatic.

Garcia, C., 2008. “Comparison of friction modelsapplied to a control valve”. Control Engineering Practice, 16(10):1231-1243.

Hägglund T., 2002.“A friction compensator for pneumatic control valves”. Journal of Process Control;12:897-904.

Hidalgo, M.C., Garcia, C., 2012. “Application and analysis of stiction estimation methods to control valves”.10th Portuguese Conference on Automatic Control.Funchal,Portugal.

Kano, M., Maruta, H., Kugemoto, H., Shimizu, K., 2004. “Practical Model and Detection Algorithm for Valve Stiction”.7th IFAC Symposium on Dynamics and Control of Process Systems (DYCOPS), Cambridge, MA, USA.

Srinivasan, R., Rengaswamy, R.,, 2005.”Stiction Compensation in Process Control Loops: A Framework for Integrating Stiction Measure and Compensation”. Ind. Eng. Chem. Res., v. 44 n. 24, p. 9164-9174.

9. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.