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EVALUATION OF THE CHARACTERISTICS OF A ROBUST MODEL-BASED PREDICTIVE CONTROL APPROACH: A CASE STUDY OF A FLOW PROCESS CONTROL WITH DEAD ZONE, NOISE AND POWER LOSS

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Abstract. *Nowadays, techniques of Model-based Predictive Control (MPC) have been widespread mainly to its ability to easily deal with physical and operational constraints of the process. Such strategies aim to minimize, each sample time, a cost function based on a mathematical model, physical and operational constraints of the process. In this paper, Dynamic Matrix Control (DMC) formulation has been studied. This approach was chosen because it is a simple and effective one. It is important to note that MPC approaches, as well DMC, are highly dependent of the accuracy of the mathematical model. However there are mismatches between the mathematical model and the behavior of the real process. Such mismatches can be caused by nonlinearities, non-modeling dynamics or even faults. In some cases those differences can cause violation of the constraints. To solve such inconvenience it is applied and extended a technique of robust MPC presented in a previous conference. Experimental simulations are appeared to well evaluating the characteristics of the proposed approach. Such characteristics include: the influence of adjusting the control parameters, the accommodation disturbances, the influence of the use of feedback filter, and the consideration of the pump dead zone with the use of constraints. Finally, it was performed a test simulating power loss fault.*

Keywords: *Predictive control; Dynamic Matrix Control; Robust Control; Uncertainty gain; Constraints.*

1. INTRODUCTION

MPC is a family of strategies that minimizes a cost function in a predefined prediction horizon. This strategy was developed originally on 70's by petrochemical research groups (Qin and Badgwell, 2002) (Camacho, 1999). Moreover, with the increase of computational power, MPC idea has been widespread in many industrial sectors (Camacho and Berenguel, 1997) (Gopinathan, *et al*., 1999) (Hamel, *et al*., 2002) (Cavalca, *et al*., 2010).

Considering such context, it is possible to highlight two approaches as: Dynamic Matrix Control (DMC) (Cutler and Ramaker, 1979) and Model Predictive Heuristic Control (MPHC) (Richalet, *et al*., 1978). In this paper, a DMC has been chosen mainly because it is simple and an effective method. Such technique uses step response of the process in order to obtain a representative mathematical model. The control loop of a flow process of the FESTO didactic workstation (MPS-PA) (Helmich, 2008) is studied.

In this paper, characteristics of DMC strategy will be analyzed, as well the influence of adjusting the control parameters. Therefore, a feedback filter will be tested. Furthermore, a nonlinear behavior, called dead zone, will be treated with adding operational constraints. Finally, a simulating pump power loss fault will be performed which satisfactory demonstrating the robustness qualities of the control loop.

The FESTO didactic workstation was triggered and controlled through software Matlab via the Object linking and embedding for Process Control toolbox (OPC) and Simulink. The FluidLab was used just to obtain the step response of the flow process. The OPC toolbox was used to make the communication computer to MPS-PA, which allows making the data acquisition .All the results showed in this paper are experimental.

Throughout the text, I represents an identity matrix, the notation (./k) is used in predictions with respect to time k, [.]n represents a matrix with n lines and 1 column, and the * superscript indicates an optimal solution.

2. DMC

In MPC field, one of the first techniques to be developed was DMC. This method uses a step response based convolution model as prediction equation. Still, in this formulation it was considered the existence of an output disturbance, which possibility that approach accommodates constants disturbances.

To understand DMC formulation it is necessary to introduce some basic concepts, such as: predict horizon (N), control horizon (M) and receding horizon (Camacho, 1999). Predict horizon is how far the system is going to be predicted. The control horizon is how far it will be applied the control action and it is related with the number of

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degrees of freedom of optimization problem. Usually $M<N$, because such condition allows to reduce the complexity of optimization problem. The result of the optimization problem is an optimal control sequence (ΔU^{*}), however only the first value is applied in the system each sample time, which is called a receding horizon.

The possible future outputs ($\hat{Y}$) for a determinate predict horizon N are predict for each sampling time using a representative mathematical model of the process, the actual measured output (y_m) and the futures control action ($\Delta\hat{U}$). However, it is applied only the first term of the optimal control sequence. In the next interaction, minimizing process is repeated using the concept of receding horizon (Matos, *et al.*, 2008).

The cost function has a quadratic form and can be written as:

$$J(\hat{Y},\Delta\hat{U})=(\hat{Y}-Y_{ref})^{T}(\hat{Y}-Y_{ref})+\rho\Delta\hat{U}^{T}\Delta U \tag{1}$$

where in:

$$\hat{Y}=\begin{bmatrix}\hat{y}(k+1|k)\\ \hat{y}(k+2|k)\\ \vdots\\ \hat{y}(k+N|k)\end{bmatrix} \qquad Y_{ref}=\begin{bmatrix}y_{ref}(k+1)\\ y_{ref}(k+2)\\ \vdots\\ y_{ref}(k+N)\end{bmatrix} \qquad \Delta\hat{U}=\begin{bmatrix}\Delta\hat{u}(k|k)\\ \Delta\hat{u}(k+1|k)\\ \vdots\\ \Delta\hat{u}(k+M-1|k)\end{bmatrix} \tag{2}$$

In which Y_{ref} is a vector of the future references. In this study, it will be considered that $Y_{ref}=y_{ref}$. Still, ρ is a weighting factor. The predict outputs can be written in function of the control sequence by $\hat{Y}=G\Delta\hat{U}+F_u$, where F_u is the free response, give by $y_m(k)+\sum_{n=1}^{N_s}[g(n+1)-g(n)]\Delta u(k-n)$. The predict equation can be written as:

$$\hat{Y}=\begin{bmatrix} g(1) & 0 & \cdots & 0\\ g(2) & g(1) & \cdots & 0\\ \vdots & \vdots & \vdots & \vdots\\ g(M) & g(M-1) & \cdots & g(1)\\ \vdots & \vdots & \vdots & \vdots\\ g(N-1) & g(N-2) & \cdots & g(N-M)\\ g(N) & g(n-1) & \cdots & g(N-M+1)\end{bmatrix}\begin{bmatrix}\Delta\hat{u}(k|k)\\ \Delta\hat{u}(k+1|k)\\ \vdots\\ \Delta\hat{u}(k+M|k)\\ \vdots\\ \Delta\hat{u}(k+M-1)\end{bmatrix}+F_u \tag{3}$$

Where $g(1), g(2) \ldots g(N_s)$ are the sampled values of the step response $g(N_s+i)=g(N_s), \forall\, i>1$. Minimizing (1) subjected to (3), it is found the optimal sequence control which is applied the receding horizon:

$$\Delta\hat{U}^{*}=(G^{T}G+\rho I)^{-1}G^{T}(Y_{ref}-F_u) \tag{4}$$

Some process has some constraints or non linearity that can bring some unwanted behavior to control loop. Include constraints in a system costs can bring some advantages, such as increase of life cycle of the actuator as reduction of maintenance. There are a several types of constraints, in this paper was studied three kinds. Such constraints were: on the variation of control action, excursion of control variable and the excursion of the process output. All these constraints can be written as:

$$\begin{bmatrix} I_M\\ -I_M\\ T_M\\ -T_M\\ G\\ -G\end{bmatrix}\Delta\hat{U}\leq\begin{bmatrix} 1_M\Delta u_{max}\\ -1_M\Delta u_{min}\\ 1_M[u_{max}-u(k-1)]\\ 1_M[u(k-1)-u_{min}]\\ 1_N y_{max}-F\\ F-1_N y_{min}\end{bmatrix} \tag{5}$$

This is a quadratic programming problem (Maciejowski, 2002).

3. DESCRIPTION AND MODELING OF THE FLOW PROCESS

Consider a flow process existent on the didactic workstation of FESTO (MPS-PA) (Helmich, 2008) as shown in Figure 1(a) and Figure 1(b). The flow control loop has as actuator a pump which works on analogical mode (*0-10V*). The liquid flows from P101 to V104, as can be seen in Figure 1(b). The data are obtained through a flow sensor B102.

(a) (b)

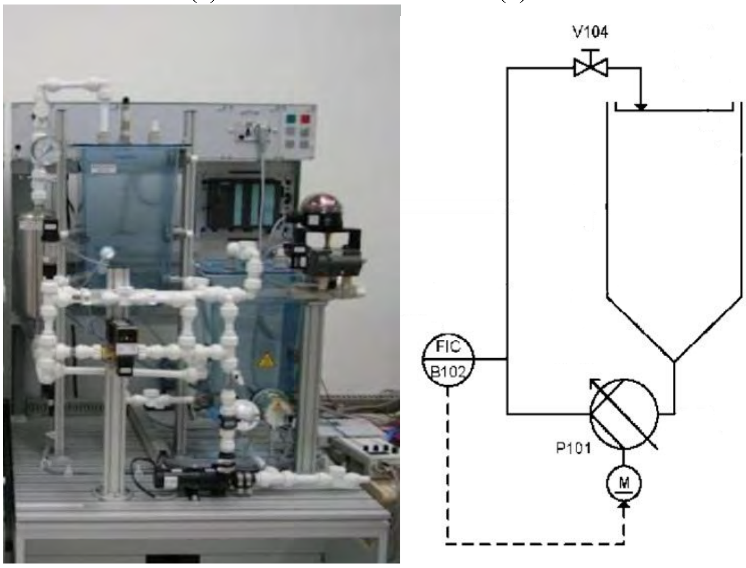

Figure 1: (a) Compact station MPS-PA FESTO and (b) Process diagram (Helmich, 2008).

The step response for a certain operational point was gotten using the software FluidLab and the EasyPort (data acquisition board) (Helmich, 2008). Such response was obtained initially putting a *5V* input in the pump. After the flow is stabilized, a step of *1V* was applied. A transfer function was obtained with the normalization and linearization of the experimental results around the operation point $\overline{V}=5V$ and $\overline{Q}=1{,}9\ L/min$. The model step response results are shown in the Figure 2.

$$G(s)= \frac{0{,}4688}{1+0{,}34779s} \tag{6}$$

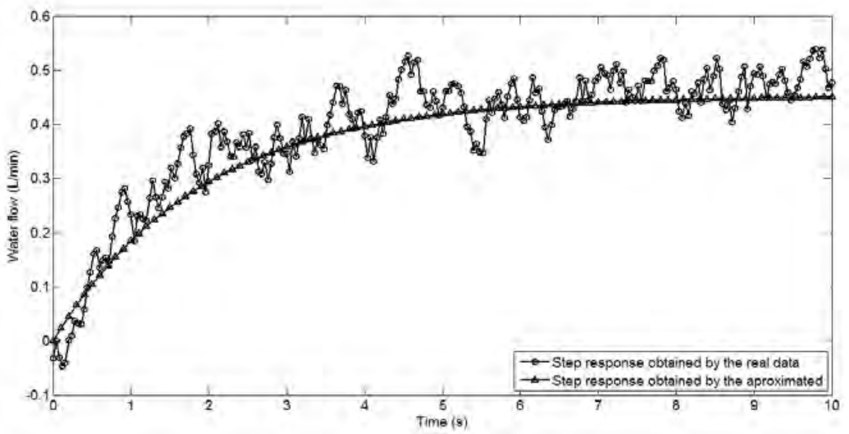

Figure 2: Step response obtained by real data and the identified transfer function.

DMC control has been applied using the step response obtained by (1) with a sample time of $T_s=0{,}1s$. The control parameters are set in $N=20$, $M=5$, $\rho=1$. Figure 3 shows the control loop response for a reference of *2L/min*. The action control is showed in Figure 4.

Looking to Figure 3 and 4 it is possible to conclude that DMC was able to stabilize the system, leading the controlled variable to the reference without steady state error. The delay showed in Figure 3 is mainly caused by a nonlinearity (dead zone) existent in the actuator.

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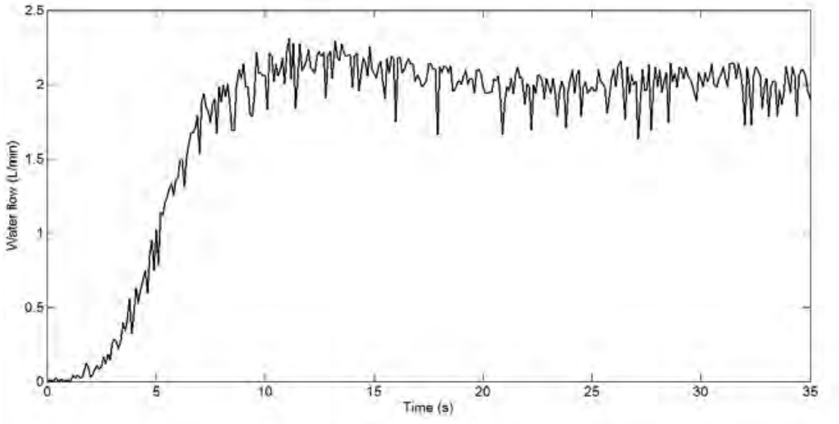

Figure 3: Flow DMC loop: controlled variable.

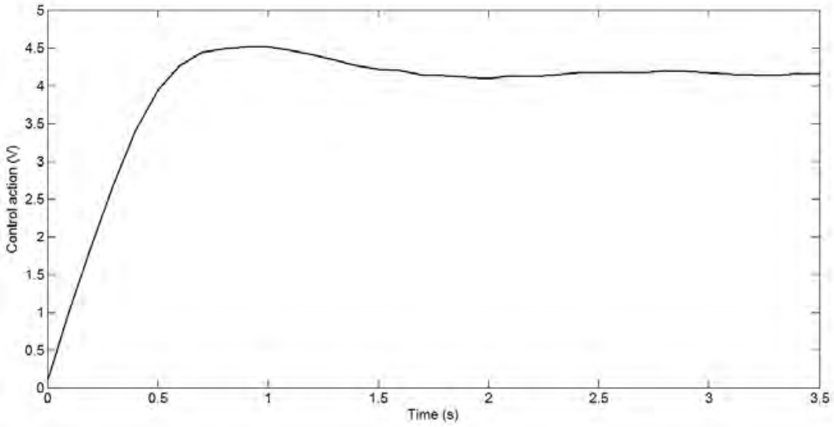

Figure 4: Flow DMC loop: manipulated variable.

4. CONTROL SETTINGS

In this section, experimental simulations will be studied evaluating the characteristics of the present approach. Such characteristics includes: influence of adjusting the control parameters, accommodation disturbances, influence of the use of feedback filter, and the consideration of the pump dead zone with the use of constraints. Finally, it was performed a test simulating power loss fault.

4.1 Influence of control parameters settings

DMC has three control parameters that can be modified to get a better behavior of the control loop: prediction horizon (N), control horizon (M) and control action weight (ρ). In order to investigate the influence of adjusting those parameters, it was kept two constant and the other one was changed. All simulations has sample time $T_s=0,1s$ and a flow reference of *2L/min*. The step reference was started in *t=1s*.

Figure 5 shows the influence of changing the control action weight between 15 and 25, keeping $N=10$ and $M=5$ constants. As can be seen, as bigger ρ, the behavior of control loop will tend to be more like a first order system. Such behavior is obtained because as bigger ρ, the variations of control action will be more penalized, resulting in a less aggressive loop.

Otherwise, when ρ=20 and $M=5$ are kept constant and is varied N, the result is shown in Figure 6. As increasing the value of prediction horizon, the system will have a more oscillatory behavior with a bigger overshoot and a lower settling time. This occurs, because with a bigger prediction horizon, the control loop can better evaluate the output trajectory and then improve the transient response.

Figure 7 shows the resulting of varying the value of M and keeping constant the other variables in $\rho=20$ and $N=30$. In this case, such parameter does not cause considerable changes on the behavior of the control loop.

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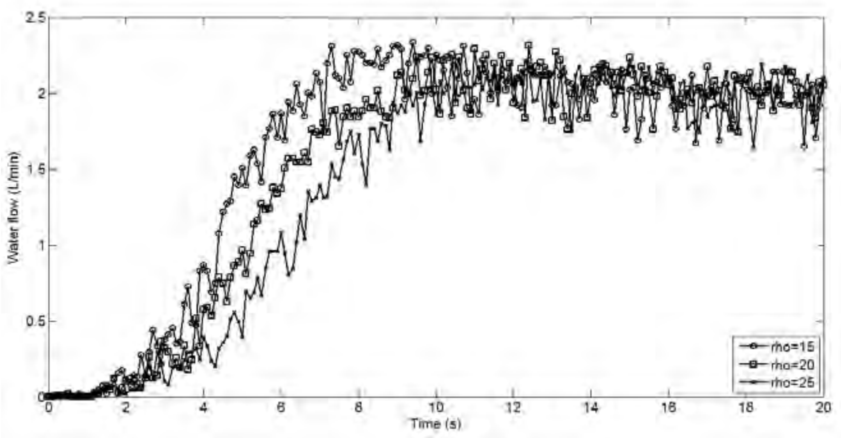

Figure 5: Influence of parameters in the system influence of ρ.

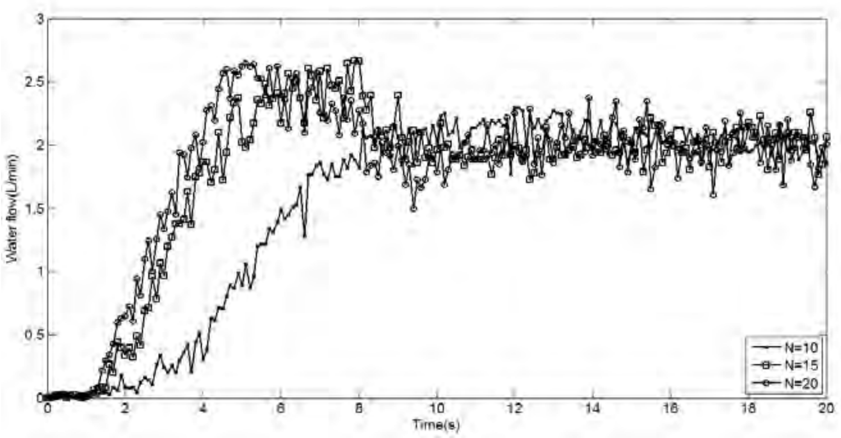

Figure 6: Influence of parameters in the system influence of N.

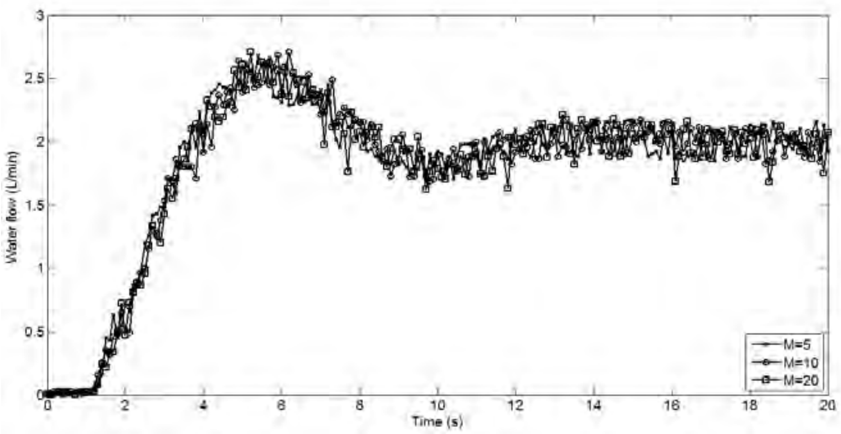

Figure 7: Influence of parameters in the system influence of M.

4.2 Disturbances accommodation

DMC strategy has capability to accommodate constant disturbance. In order to verify this characteristic, the opening of valve V104 was changed. The test starts with the valve completely open, then in $t=4,6s$ the valve is slightly closed. Figure 8 and 9 shows the result of this test.

When the valve is slightly closed it is natural that flow decreases. Therefore, in order to the output of the control loop comes back to the reference it is necessary that control action value increases. The control action behavior is shown in Figure 9.

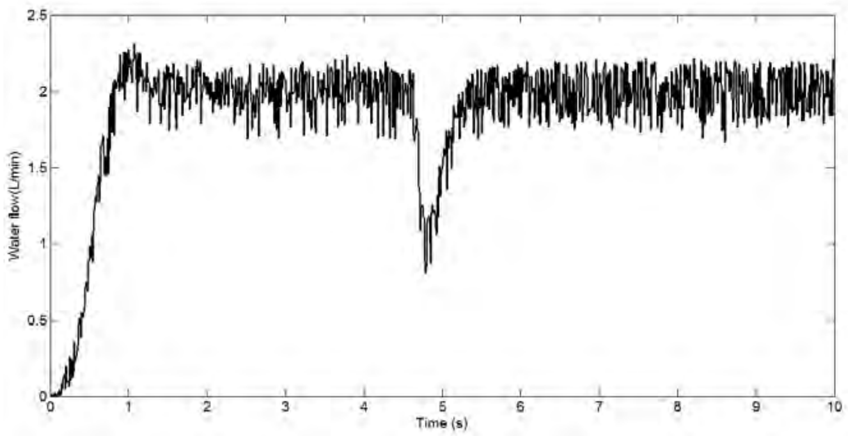

Figure 8: The system response when occurs a disturbance in the opening of V104.

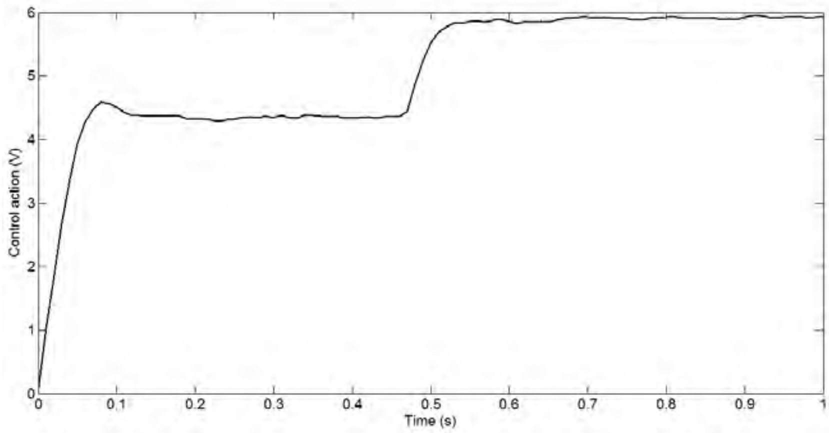

Figure 9: The control action when occurs a disturbance in the opening of V104.

Finally, it important to note that the scheme used in all simulations does not consider the normalization around of the operational point. The control scheme that accurately represents the obtained mathematical model with normalization around of the operational point, requires that initially the process was took to the operational point, as well the inclusion of the constants $\bar{V}$ and $\bar{Q}$.

In this work, such operational points considerations are despised. Then mainly influences are partly treated as disturbances ($\bar{V}$ and $\bar{Q}$) and elsewhere as non modeling dead zone (which will be later be treated as a constant).

4.3 Feedback filter

As is possible to see in the flow in the present results, the flow measurement has a high frequency noise. In this section a filter will be included in the feedback loop. Such filter was implemented using the Matlab Simulink environment and connected with the real process using the OPC. A low pass feedback filter was designed as (Sedra, 2004):

$$T(s)=\frac{0,9}{s+0,9} \tag{7}$$

Figure 10 makes a comparison between the system with and without a feedback filter. As can be seem, the filter includes an initial delay in the control loop. But both results show that the accommodation time is similar. Anyway, in order to include the filter behavior a new step response model was obtained.

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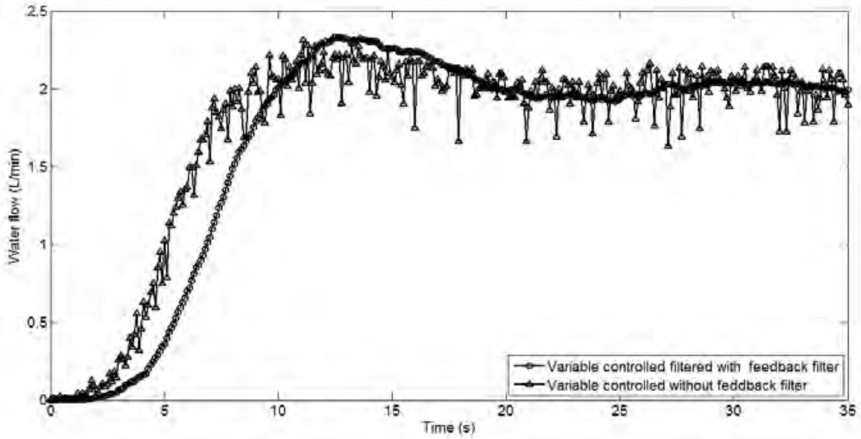

Figure 10: Comparison between the system with and without a feedback filter.

The filter influence was analyzed in a DMC loop with the control parameters set in $N=10$, $M=5$, $\rho=20$ and sample time $T_s=0,1s$. Comparing Figure 3 and 11 as can be seen, the filter did not show relevant changes in the output variable behavior. However, it has a considerable influence on the control action, as showed in Figure 12 and 13. In this case, the steady state value is similar, but the control action with a feedback filter becomes smoother. Still, it is possible to use that the maximum value of the control action without filter is *5,5V* and with a feedback filter is *4,5V*. To the next analysis steps will be used the feedback filter.

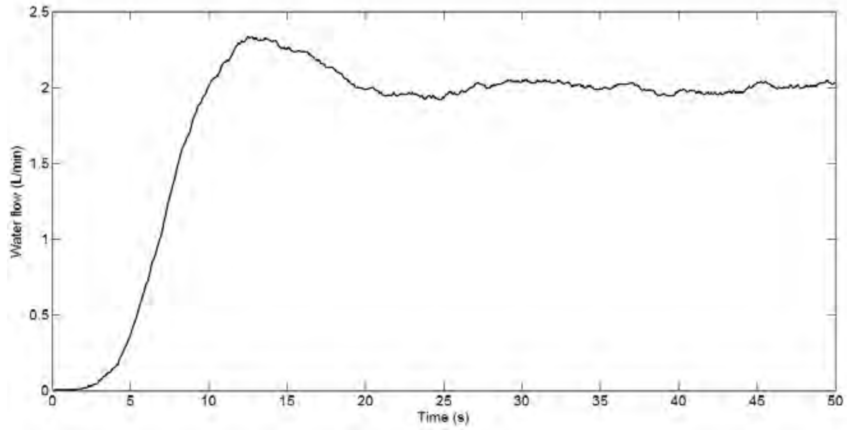

Figure 11: Filter output.

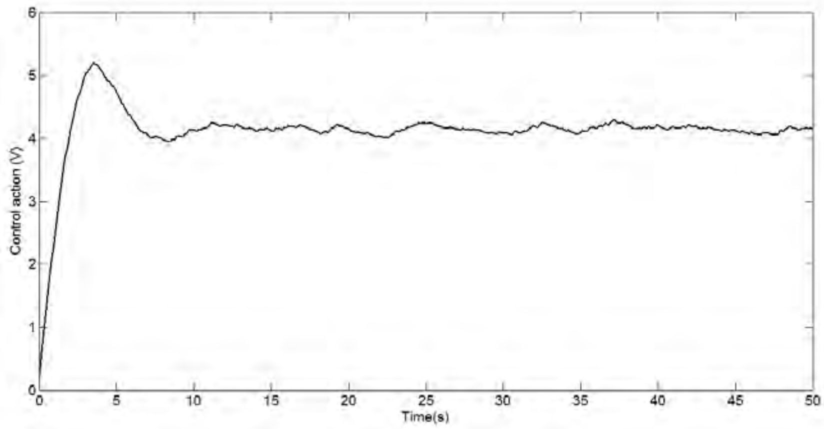

Figure 12: Control action: without feedback filter.

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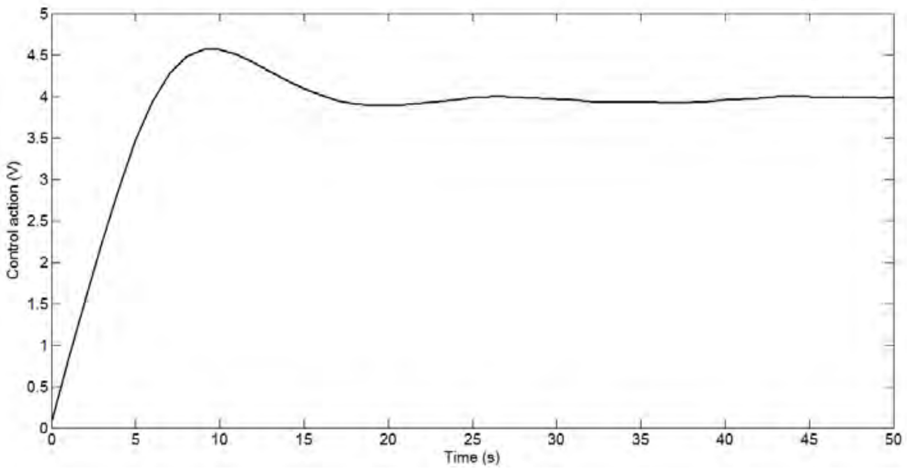

Figure 13: Control action: with feedback filter.

4.4 Dead zone treatment using constraint control

Observing all the simulations, it is possible to notice there is a delay in the beginning of the controlled variable response. This delay is mainly caused by a dead zone in the pump and as well the fact that the operating point setting is disregarded. In order to verify this non linearity was made a simulation based on set some voltages on the actuator and then check the value of flow. As result, there are some voltage values that the pump force does not overcome the gravity and then there is not liquid flow. Figure 14 shows a study which explains this dead zone.

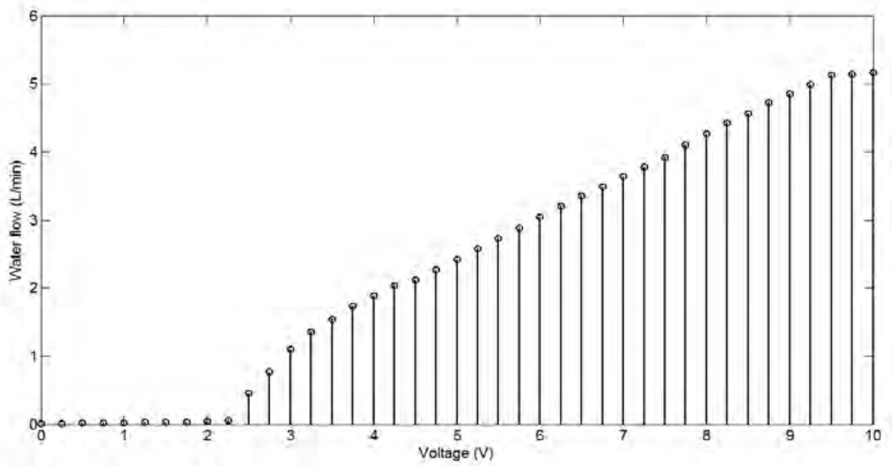

Figure 14: Pump dead zone.

This test was accomplished in open loop, it was noted when it is applying 0 to $2{,}25V$ to the pump there is no liquid flow in the process, like is shown in Figure 14.

Therefore, to reduce the dead zone influence will be added a constraint in the control loop given by:

$$2{,}5V \leq u \leq 10V \tag{8}$$

The solution of the quadratic program was obtained using the *quadprog* Matlab function.

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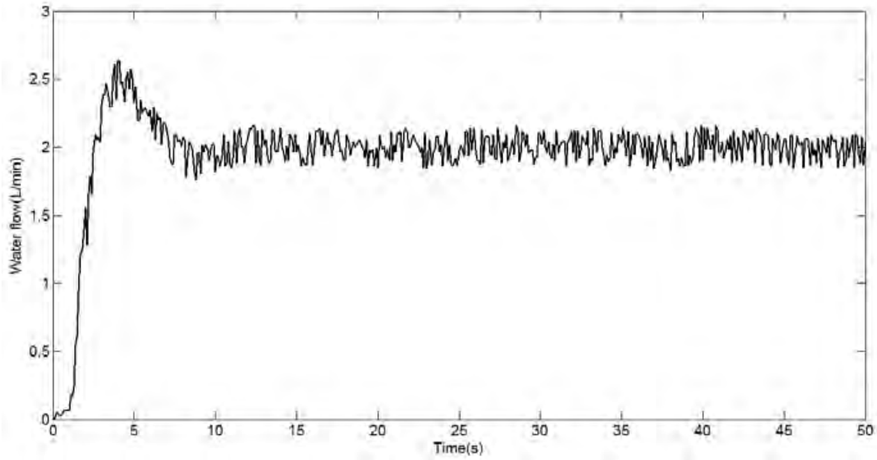

Figure 15: System output when applied constraint (8).

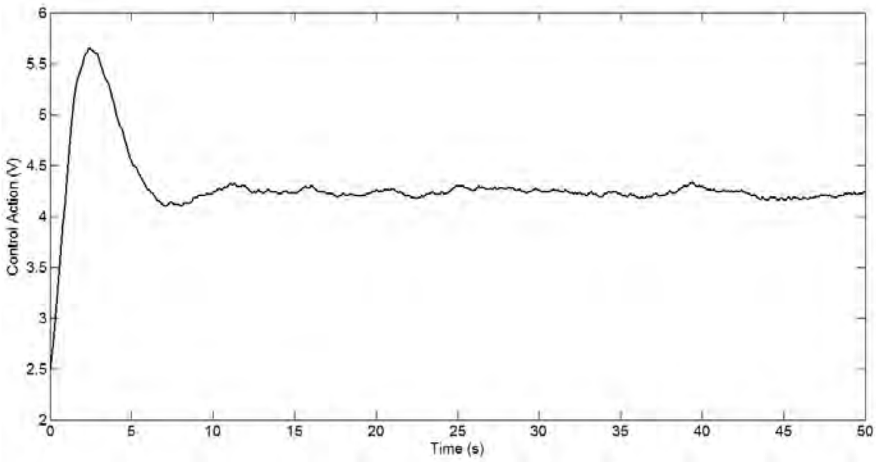

Figure 16: Control action when applied constraint (8).

Figures 15 and 16 shows the experimental results with control parameters set in $N=10$, $M=5$ and $\rho=10$ and applying the constraint (8). Furthermore, when was used this constraint formulation the dead zone influence was removed.

4.5 Uncertainly gain treatment using a robust approach

Finally, in this section will be simulated a pump power loss fault. Consider that there is a control gain K which is assumed to belong to the interval $[\varepsilon_{min}K, \varepsilon_{max}K]$. If it is employed a control sequence which respects the extreme values of such constraint, then will be respected to intermediate values as well (Camacho, 1999) (Matos, *et al.*, 2008). To introduce this uncertainty in the control loop it is been necessary to change the constraint (5), adding an uncertainty variable ε which is given by:

$$1_M[u_{min}-\varepsilon^*u(k-1)]\leq\varepsilon^*T_M\Delta\hat{U}\leq 1_M[u_{max}-\varepsilon^*u(k-1)] \quad (9)$$

Such approach is similar to (Matos, *et al.*, 2008) but in this study case was included uncertainties in control action constraints. In order to evaluate the proposed robust approach, it was assumed a gain uncertainty interval between $\varepsilon_{min}=0,9$ and $\varepsilon_{max}=1$.

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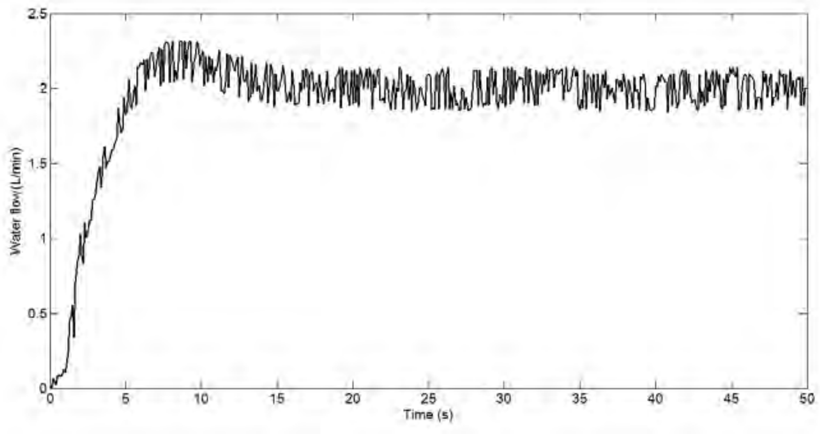

Figure 17: System output when it is applied constraint and simulated a power loss.

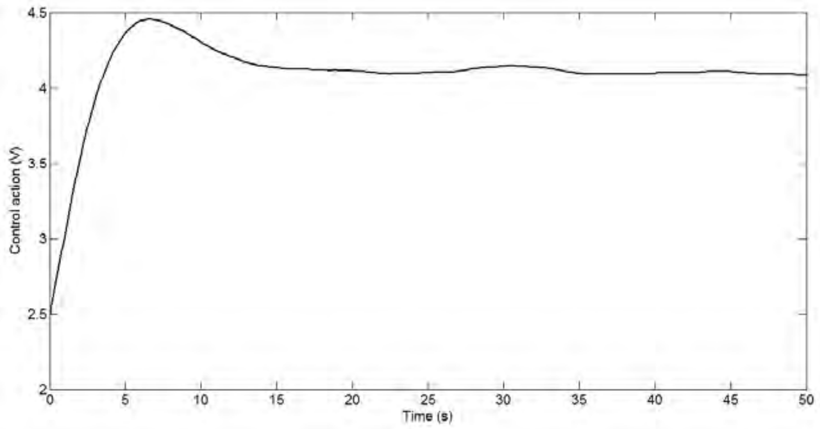

Figure 18: Control action that is applied in the system.

To simulate the power loss fault, it was considered that pump was operating with 10% of power loss. The controller parameters are set in $N=10$, $M=5$, $\rho=20$ and $T_s=0,1s$. The control action constraint is set as (8). The simulation results are shown in Figure 17 and Figure 18.

Although there is loss power fault in the water bomb, the DMC controller can stabilize the system and still respecting the initially constraint imposed. The Figure 19 shows the control action calculated by DMC controller.

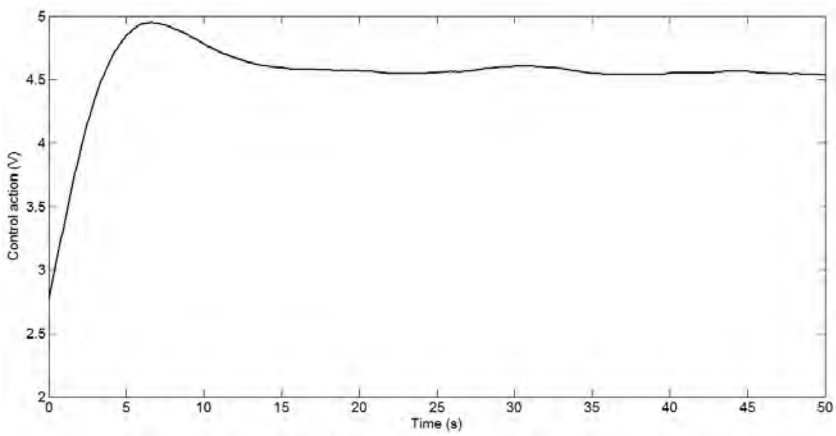

Figure 19: Control action calculated by DMC controller.

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Due to uncertainty gain, which was included in the action constraint, the DMC controller already knows that is possible to have a variable gain. Therefore, the optimal control action has an increasing in its value in order to even with up to 10% of power loss. As expected, the action control calculated has the maximum value set in *4,95V*. However the control action applied to the system, after the power loss, is showed in Figure 18 and has the maximum value set in *4,4V*.

The constraints are respected because the uncertainty gain was included in the quadratic optimization problem. If was set $\varepsilon_{min} = \varepsilon_{max} = 1$ and simulated the same loss power fault, the constraint imposed are not respected anymore, as Figure 20 shows.

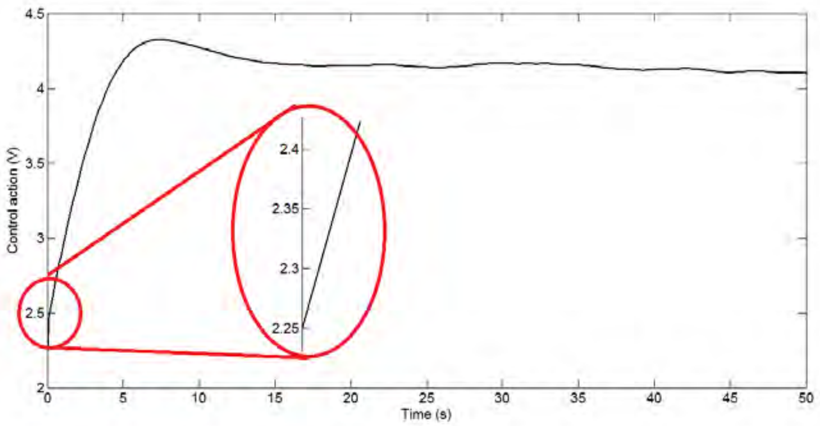

Figure 20: Control action calculated by DMC controller when the constraint is not respected.

In this case, the minimum constraint is not respected and the control action has the initial value set in *2,25V*. In this case the value applied in the control loop is even smaller because the pump has 10% of low power, then the constraint is not respected and the dead zone return to influence the control loop.

5. CONCLUSIONS

In this paper was studied MPC approaches, given emphasis in DMC strategy. In the beginning was made a study which the mainly goal was learn about the theory involved in MPC strategy. For the practical part, was chosen the DMC strategy because it is a simple and effective one. The process chosen was the liquid flow process of a FESTO didactic workstation. It was investigated the influence of adjusting the control parameters, as well it was illustrated DMC disturbance accommodation characteristics. A feedback filter improved the dynamic of the process and brings a control smoothly. With the constraint theory was possible eliminate the dead zone influence in the pump. Finally, was simulated a power loss fault. Such fault was deal with including an uncertainty, using the concept of robust control and fault tolerance. The obtained results were satisfactory experimental evaluating DMC characteristics.

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