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Analysis of Constraint Modification in Model-Based Control Valve Stiction Compensation

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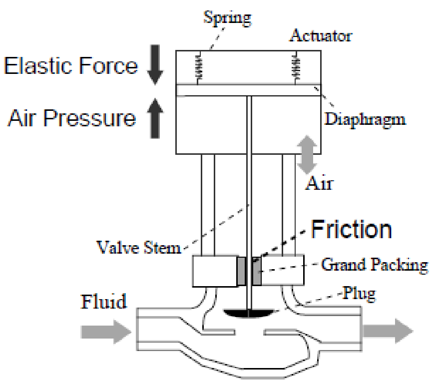
Graphical Abstract



Abstract

A model-based stiction compensation algorithm has been developed based on the H. Zabiri *et al*. Mixed Integer Quadratic Programming (MIQP) model predictive controller (MPC) algorithm which uses optimization to compensate for backlash in actuators. MIQP-based MPC shows promising result for stiction compensation. However, the backlash compensation formulation alone can remove oscillation caused by stiction dead-band but fails to reduce the offset caused by stiction slip-jump. Several modifications are proposed to solve the offset issue. The MIQP optimization problem constrains were loosened to give more flexibility to the optimizer. Simulation studies were conducted using a 2x2 distillation column model. With loosened constraints, MIQP based MPC reduced the offset at the expense of introducing oscillation into the system.

Keywords: Stiction, MIQP, MPC, backlash, optimization

Abstrak

Algoritma pampasan geseran statik telah dikembangkan berdasarkan kajian H. Zabiri *et al.* yang menggabungkan kontrol model ramalan (MPC) dan pengaturcaraan kuadratik bilangan bulat bercampur (MIQP) bagi mengira gerakkan optimum injap kawalan. Formulasi pampasan seadanya mampu menghilangkan sebahagian daripada kesan geseran statik. Bagi mempertingkatkan keberkesanan formulasi, kekangan formulasi MIQP telah dilonggarkan. Kajian simulasi telah dijalankan menggunakan model kolum penyuling 2x2. Kelonggaran kekangan telah mengurangkan ketidakselarian tetapi telah menyebabkan osilasi.

Kata kunci: Geseran statik, MIQP, MPC, pengoptimuman

1.0 INTRODUCTION

Control valve stiction is a common problem found in the industry. Routine operation is affected by this problem which can only be resolved by replacing the valve packing during periodic plant shutdown. Stiction causes poor control loop performance by introducing oscillation in the process variables which can result in severe fluctuations of the set point. The effects can trickle down to other processes in the plant [1] affecting the product quality and plant economy. Studies have shown that stiction is the most common control valve nonlinearity affecting 20 – 30 % of control loops [2; 3].

The term stiction term refers to combination of two words, static and friction. Due to excessive static friction at the valve packing, the valve stem in losses the ability to travel smoothly to reproduce the movement corresponding to the input signals by the controller.

The negative impact caused by stiction to the control loop can be minimized by stiction compensators. There are a number of compensation methods but methods using the optimization approach are scarce. H. Zabiri *et al.* proposed Mixed Integer Quadratic Programming (MIQP) based Model Predictive Controller (MPC) that uses optimization approach compensation to compensate for the effects or control valve backlash. Further investigation on this MIQP-based MPC could extend its functionality to compensate stiction nonlinearities.

This paper reworks the orignal MIQP-based MPC formulation and investigates its effectiveness as a stiction compensator.

1.1 Stiction Modeling & Simulation

Sticiton can be modeled using a phycical model or an empirical model. Since the physical model requires the knowledge of several parameters which are difficult to measure, the empirial method is frequently used in simulation. The two-parameter model proposed by Choudhury *et al.*, formulated using an input-output plot of a sticky valve is considered to be sufficiently accurate [4]. A typical plot of the movement of a sticky valve is shown below in Figure 1.

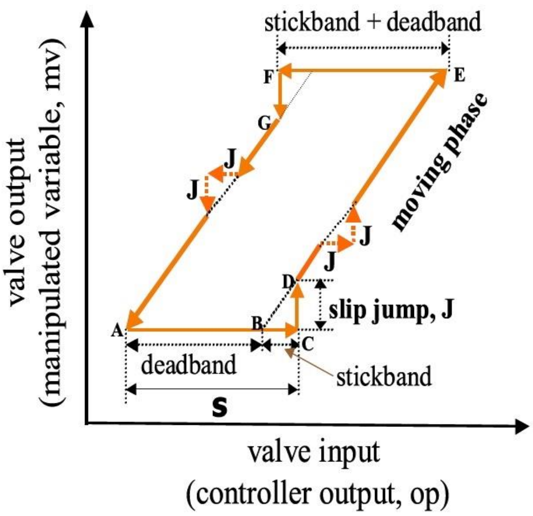


Figure 1 Input-output plot of stiction valve [4]

Stiction has four main components that describes its characteristics; deadband, stick-band, slip-jump and moving phase.

A sticky valve will not immediately move when a change in direction at point A is applied. Despite of the valve input given, the valve will remain stuck due to the static friction. The valve produces a jump movement once the input signal given to the valve overcomes the static friction. The magnitude of signal needed to overcome the static friction, S is equal to the deadband (AB) plus the stick-band (BC).

The magnitude of jump, J is denoted as slip-jump (CD) as shown in Figure 1. Moving phase described the valve linear movement once it has started its movement with a slip-jump. The sticky valve is predicted to stick again during the moving phase however, the magnitude of static friction that will be needed to overcome again will be the stick-band (BC) only to ensure continuous movement. This valve movement characteristics replicates during the reverse movement of vale form point E to A as shown in Figure 1. Slip-jump occurs due to the sudden conversion of the accumulated potential energy given to the valve as input signal to kinetic energy [4].

1.2 Stiction Compensation

Sticky valves can be fixed by replacing the packing. However, repair and maintenance requires process operations to be halted for the valve to be taken out of service, dismantled and refitted. Therefore stiction compensators can be very helpful during this period to mitigate stiction negative impact till the next maintenance schedule [5].

Stiction compensators can be classified into model based and non-model based. Both types requires stiction parameters to be defined [6]. Model-based compensators incorporates controller model and process model in designing the compensator signal [7]. There are well known methods or strategies for stiction compensation, compensation through controller tuning [8; 9], knocker singal method [10], constant reinforcement [11], alternate knocker method [12], two or three move compensators [7] and optimization approaches [7; 13].

1.3 Principles of MPC

Model Predictive Control (MPC) aims to prevent violations of input and output constrains, guide certain output variables to their optimal set points while keeping other output within a specific range. It prevents aggressive movement of input variables. [14]. Similar it's predecessorr Internal Model Controller (IMC), a process model is used in MPC to predict the current values of output variables [15]. The predicted values are compared with the measured actual values to obtain the error that is sent to the prediction block through feedback loop. Input and output constrains can be incorporated in the MPC prediction calculations. The calculations generates solution to both servo and regulatory problems in the system [16].

MPC differs from IMC by incorporating constrains in their solution. Usually as objective function is used to maximize or minimize the selection criteria so that an optimum values of set points are achievable. The optimum value of set point are based on constrains included in the objective function. Therefore MPC always uses optimization approach in generating the control solution. The control calculations are done based on current measurement and predictions of the future values of the outputs. Dynamic model is used to calculate the predictions. Ultimately, MPC determines a sequence of control actions to optimize the predicted response movement to the set point. A special feature in MPC is its receding horizon. From the sequence of control action that is develop only the first move is implemented in the system and new sequence of control action is developed according to the predicted response and error in the receding horizon [16; 17].

2.0 METHODOLOGY

2.1 Stiction Compensation using Dead-band Compensator

Stiction and backlash both have a deadband component. However, stiction also has slip-jump on top of deadband. The MIQP-MPC is a combination of a standard MPC solving for the optimal control move and a set of binary constraints to compensate for backlash. Presence of backlash activates the mixed-integer functionality in the MIQP-MPC thus compensating the backlash. Since the MIQP-MPC does not have a stiction model integrated into it, purely deadband alone is used to compensat for the stiction problem. The MIQP-MPC was tested by varying a range of deadband values given to compensate for the same case of stiction. The idea is either to undercompensate or overcompensate with deadband alone for stiction nonlinearities using purely the MIQP backlash compensation formulation.

2.2 Manipulation of MIQP-based MPC Activation Time

Modification proposed was manipulating the activation time of the MIQP-MPC for the same type of stiction cases. Activation time denoted as Ts, is a setting in the MIQP-MPC whereby it is the time when the MIQP functionality activates in a normal MPC. Particular time frame is waited for the MIQP activation in the MPC. During this period the normal nonlinear MPC rectifies the process using the process model integrated within its structure. However, when backlash is present during the time frame the MIQP functionality activates after the fixed timeframe. The reason for such a setting in the controller is to prevent compensating for backlash nonlinearities during its absence. MIQP formulation incorporates the inverse model of the backlash nonlinearity. Therefore, the proposed method was to delay the MIQP formulation activation time so that the linear MPC will eliminate the offset due to slip-jump stiction nonlinearities. Upon MIQP activation the oscillation due to deadband stiction can be removed completely.

2.3 Mixed Integer Quadratic Programming (MIQP) based MPC

Backlash is a another nonlinear problem that occur in actuators and Zabiri *et al.* develop a Mixed-Integer Quadratic Programming (MIQP) based model predictive controller (MPC) to compensate and improve control loop performance. In this approach, a data driven backlash model was applied. Similarly, an optimization formulation was develop based on a Mixed Integer Quadratic Programming (MIQP) optimization problem. The solution is incorporated with all the backlash data from the model. Based on simulation and experiments, MIQP based MPC effectively avoids the deadband region of backlash thus improving the control loop performance [18]. The MIQP problem takes the form below [19; 20]F:

$$\begin{aligned} \min \quad & z^T Q z + b^T z \\ s.t. \quad & Cz + \bar{d} \leq 0 \\ & z = \begin{bmatrix} z_c \\ z_d \end{bmatrix} \\ & z_c \in \mathbb{R}^{n_c} \\ & z_d \in \{0,1\}^{n_d} \end{aligned}$$

The obejctive is to find vector z such that the function is minimised. Matrix *Q* is a square matrix of weights and *b* is a vector of input variables. Variables z_c and z_d represent the continuous part and the discrete part respectively. The discrete part itself is not actually in the form of numbers but is in the form of Boolean variables. This allows logical expressions to be written as algebraic constraints which the solver can use to compute the optimum control moves. When z_d is 0, the additional constraints to compensate are inactive. The additional constraints can be activated by switching z_d to 1.

2.4 Loosening Constains of MIQP Optimizer

Current backlash compensation algorithm incorporates the backlash inverse function in the form of linear inequalities. Both backlash and stiction effect is present and observed only for a certain range of controller output. Changes or input value anything greater than the certain range of controller output which is the deadband range can avoid the effects of backlash and stiction.

Mixed Integer Quadratic Programming (MIQP) is a type of mathematical programming that presents the constrains in the form of logical selection criteria rather than the typical mathematical model incorporated with constrains parameters approach [18; 21]. Therefore using the inverse of the backlash function in the form of linear inequalities, the MIQP optimizer avoids the deadband thus compensating for the effects of backlash.

Constrains are developed in the MIQP optimization problem using the inverse function of backlash to guide the selection of controller output to avoid the deadband. The constraints are formulated as shown below.

$$\begin{aligned} &\Delta u_i(k) - d_i \geq \left(\overline{u_{\iota_{min}}} - d_i\right)(1 - \delta_{i1}) \\ &\Delta u_i(k) - d_i \leq \left(\overline{u_{\iota_{max}}} - d_i\right)\delta_{i1} \\ &\Delta u_i(k) + d_i \geq \left(\overline{u_{\iota_{max}}} - d_i\right)(1 - \delta_{i2}) \\ &\Delta u_i(k) + d_i \leq \left(\overline{u_{\iota_{min}}} - d_i\right)\delta_{i2} \\ &\Delta u_i(k) \geq \overline{u_{\iota_{min}}}\,(1 - \delta_{i3}) \\ &\Delta u_i(k) \leq \overline{u_{\iota_{min}}}\,(1 - \delta_{i3}) \end{aligned}$$

where

$$\overline{u_{i_{min}}} = u_{i_{min}} - u(k-1)$$
$$\overline{u_{i_{max}}} = u_{i_{max}} - u(k-1)$$

The algorithm modification proposed was to loosen constrains by a certain range of values. To enable flexibility to the optimizer. The current persisting problem to the MIQP-MPC under stiction compensation is the disability to remove offset. The offset is present due to the inability of the controller to provide the optimized solution.

Model Predictive Controllers uses optimization approach and the solution is restricted to the constrains. Therefore, if the constraints are too tight i.e. the specified operating region is too small, MPC has the tendency to reject certain possible solution.

Modifying the optimization by loosening the constrains would give more flexibility to the optimizer to choose from a wider range of possible control moves to avoid the deadband region and keep process output stready

2.6 Application to Distillation Column

The case study used is the Wood and Berry distillation colummn, a two-by-two binary system [22]. The Simulink model is shown in Figure 2. The model is a first order plus time delay (FOPTD) sytem specfied by the authors as follows:

$$G(s) = \begin{bmatrix} \dfrac{12.8e^{-s}}{16.7s+1} & \dfrac{-18.9e^{-s}}{21s+1} \\ \dfrac{6.6e^{-7s}}{10.9s+1} & \dfrac{-19.4e^{-3s}}{14.4s+1} \end{bmatrix}$$

The stiction compensation simulation requires a process to analyze the effect of stiction before and after compensation by observing the changes it brings to the process variable. The manipulated variables are reflux flow rate and reboiler steam flow rate. The corresponding responding variable are top product and bottom product composition.

For this project purposes, it is assumed that no disturbance affects the system, therefore changes in the reflux flow rate will cause changes to the top product composition through the direct transfer function and changes to the bottom product composition through the interaction transfer function. Stiction model is used to simulate the behavior of a sticky valve. It is placed at input 2 which is the reboiler steam flow rate. Step input change is introduced to the system to observe the stiction effects to the output variable. The whole process is simulated for 200 minutes. Sampling time is every 1 minute for the controller and the non-linearity. Ideally, for a step input introduced to the system, the process output will fluctuate tremendously producing large overshoot.

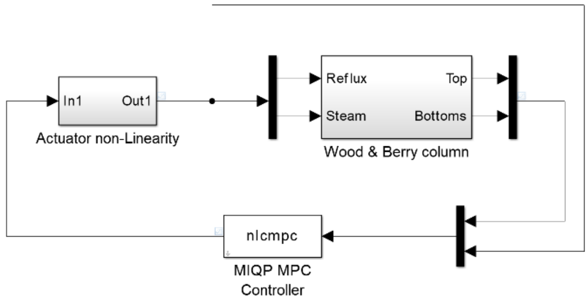


Figure 2 Simulation model of control system with process

However, the controller using its control algorithm calculates the error form the process and rectifies the process by introducing some change using the manipulated variable. The changes introduced by the controller produces inverse effect from the initial step change introduced thus cancelling each other and bringing the process output variable back to its set point. The controller used should be able to bring the process output to its new set point this is because the initial change that was introduced to the system was a step input change.

2.7 Simulation Algorithm

This paper aims to extend the application of MIQP-MPC to compensate stiction nonlinearities in control loop. The algorithm shown above have similar methodology as used for backlash however it has been altered to fit for stiction problem. Several stiction problems are simulated using MATLAB by manipulating the stiction parameters.

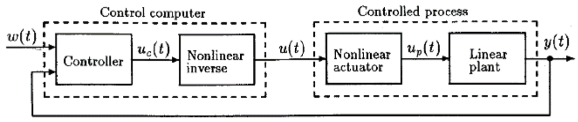


Figure 3 Backlash compensation strategy [18]

Figure 3 shows diagramatically how the conpensation is implemented. As previously explainmed, pre-defined constrains are included while formulating the optimization problem. Constrains ensure the optimal solution meets the required process consctaints. Upon including constrains, the optimization problem converts to a mixed-integer linear inequalities involving a quadratic objective function.

An MIQP algorithm is used to solve the optimization problem. The compensatoin strategy is shown in Figure 3. The changes or the compensation is implemented and the control loop performance is monitored. If it performs poorly then the whole process is repeated again else the flow end and the effectiveness of MIQP based MPC is evaluated. Based on the performance of process output response the effectiveness of the MIQP based MPC stiction compensator is evaluated and compared with other stiction compensators.

3.0 RESULTS AND DISCUSSION

3.1 Stiction Compensation using Dead-band Compensator

Since stiction and backlash share the same deadband characteristics, the MIQP-MPC was used to compensate for stiction and its effectiveness evaluated. The MIQP-MPC was tested by varying a range of deadband values given to compensate for the same case of stiction. The slip-jump parameter of stiction introduced to the MIQP-MPC in this simulation. Only the the deadband value is supplied. Below are the simulation result obtain from MATLAB and GAMS.

The results, tabulatedd in Table 1, show that a constant offset is present when MIQP-MPC is used to compensate for stiction. The set point for both outputs were set to zero. The offset amount increases for stiction undershoot cases and is worst for stiction overshoot cases. This is because the difference between backlash and stiction phenomenon is the slip-jump characteristic. The MIQP-MPC is not integrated with the stiction model therefore it does not recognizes the slip-jump occurrences. This slip-jump is expected to produce the constant offset even after compensating for the stiction deadband. The scenario becomes worse when the slip-jump value increases. Oscillations from the output are however removed in all three stiction cases.

Table 1 Offset produced using MIQP backlash MPC on stiction

Given dead-band values to controller	Offset					
	undershoot		no offset		overshoot	
	S=2, J=1.5		S=2, J=2.0		S=2.0, J=3.5	
diffuk	Output 1	Output 2	Output 1	Output 2	Output 1	Output 2
0.5	1.2625	-3.0532	0.9835	-2.4114	1.1575	-3.0882
1	1.2625	-3.0532	0.9835	-2.4114	1.1575	-3.0882
1.5	1.2625	-3.0532	0.9835	-2.4114	1.1575	-3.0882
2	1.2625	-3.0532	0.9835	-2.4114	1.1575	-3.0882
2.5	1.2625	-3.0532	0.9835	-2.4114	1.1575	-3.0882
3	1.2625	-3.0532	0.9835	-2.4114	1.1575	-3.0882
3.5	1.2625	-3.0532	0.9835	-2.4114	1.1575	-3.0882

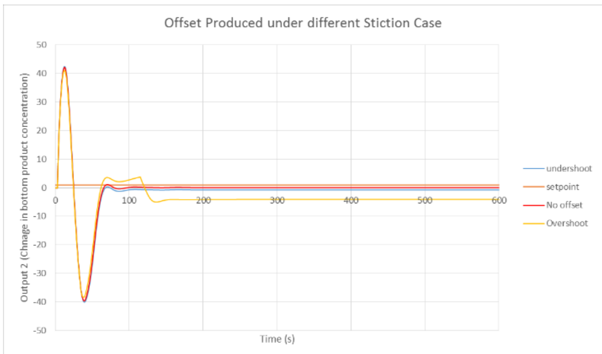


Figure 4 PV of Output 2 for various stiction case

As seen in Figure 4,the MIQP-MPC takes longer time to remove oscillation for larger slip-jump values. From the data obtained MIQP-MPC cannot complete remove the offset due to stiction however compensates for the oscillation induced.

3.2 Manipulation of MIQP based MPC Activation Time

Results show that increasing activation time does not reduce offset for slip-jump values smaller than deadband, however it reduces for larger slip-jump values. The initial activation time used for backlash compensation was 35 minutes. The simulation was conducted with range lower and higher values than 35 minutes. The offset induced by higher slip-jump values are rectified by the nonlinear MPC overtime by using the process model. Observations on the output shown in Table 2 and Figure 5 show that despite reducing the offset the longer activation time induces longer oscillation into the system. This is because the MPC is unable to rectify the oscillation induced by the deadband and the MIQP is activated later to remove the oscillation.

From the data obtained increasing the activation time does reduce the offset for larger slip-jump values however it induces longer oscillation into the system. The MPC provides solutions or operates the value in the deadband range thus inducing oscillations into the system. Oscillations are removed when MIQP activates because the MPC provides a control move which avoids the deadband region.

Table 2 Offet produced for varying Ts

Activation Time	undershoot		no offset		overshoot	
	S=2, J=1.5		S=2, J=2		S=2, J=3.5	
Ts	Output 1	Output 2	Output 1	Output 2	Output 1	Output 2
0	23.8386	-43.8851	23.7611	-43.7391	23.5286	-43.3013
10	23.6503	-43.5304	23.5727	-43.3843	23.3398	-42.9459
20	21.5436	-39.5637	21.4387	-39.3664	21.1243	-38.7743
35	0.9209	-0.734	0.4859	0.0852	2.6938	-4.0721
50	7.156	-12.4739	6.9334	-12.0548	6.3129	-10.8863
70	7.0727	-12.317	6.839	-11.8769	6.1828	-10.6413
100	0.5464	-0.0289	1.4099	-1.6547	2.8883	-4.4384
200	1.6722	-2.1485	2.0697	-2.8969	1.9182	-2.6117
300	1.0399	-0.9581	1.8264	-2.4389	2.8462	-4.359
400	1.5986	-2.0099	1.9108	-2.5978	2.9921	-4.6337
500	1.5401	-1.8998	1.9749	-2.7185	3.0767	-5.793
600	1.3424	-1.5276	1.9171	-2.6104	3.0784	-5.7962

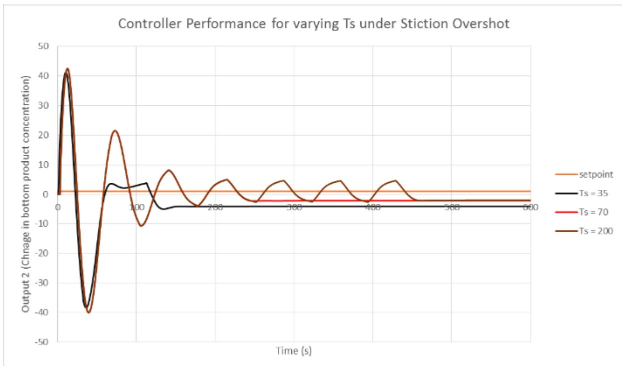


Figure 5 PV of output 2 for varying Ts under stiction overshoot

3.3 Loosening Constrains of MIQP Optimizer

Simulation results show improvement in offset reduction through constrain loosening. However, oscillation are induced in the process output variable. This is because loosening constrains will allows the controller to operate or produce solution within the deadband region.

Previously constrains were developed to avoid the controller producing output in the deadband region. Therefore, by operating in the deadband region will introduce oscillation into the system that is observed at process output. Offset is reduced because of the additional flexibility given to the optimizer to choose from a wider range of solution which leads to reduction in offset. Constrains are loosen by a range of plus-minus values.

Table 3 and Figure 6 show the result of offset reduced corresponding to the factor used.

Table 3 Average offset produced by loosening constrains

	undershoot		no offset		overshoot	
	S=2, J=1.5		S=2, J=2		S=2, J=3.5	
factor	Output 1	Output 2	Output 1	Output 2	Output 1	Output 2
0	1.2625	-3.0532	0.9835	-2.4114	1.1575	-3.0882
0.1	0.0015	-1.0313	-0.0118	-0.9454	0.1884	-0.3869
0.2	-0.1098	-0.5852	-0.0723	-0.4692	0.1387	-0.0337
0.3	-0.1176	-0.3213	-0.0693	-0.2143	0.1442	0.1485
0.4	-0.1072	-0.231	-0.0578	-0.1374	0.135	0.1648
0.5	-0.1072	-0.2298	-0.0578	-0.1374	0.135	0.1648
0.6	-0.1072	-0.2298	-0.0578	-0.1374	0.135	0.1648
0.7	-0.1072	-0.2298	-0.0578	-0.1374	0.135	0.1648
0.8	-0.1072	-0.2298	-0.0578	-0.1374	0.135	0.1648
0.9	-0.1072	-0.2298	-0.0578	-0.1374	0.135	0.1648
1	-0.1072	-0.2298	-0.0578	-0.1374	0.135	0.1648

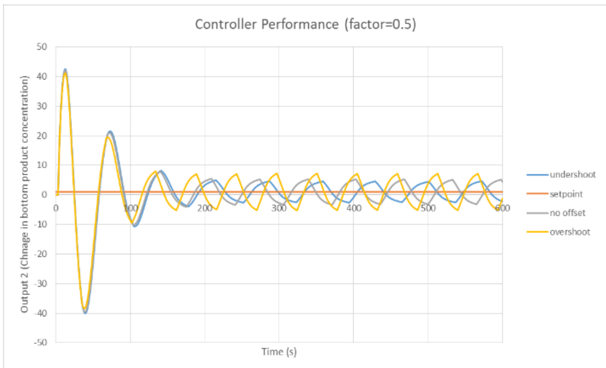


Figure 6 PV of Output 2 (f=0.5) under varying stiction case

3.4 MPC Controller Effectiveness

Efficiency of the controller is evaluated based on the ability to reduce offset and remove oscillation from process output variable. The modified controller of MIQP-MPC produced for stiction, is compared together with two other controllers that are, standard MPC and the MIQP-MPC.

The effectiveness evaluated ensures the modified controller credibility as a better solution for the stiction. Table 4 summarizes the performance of three MPC configurations compared using the process output variable through simulations. Output 2 is directly affected by the sticky valve and Output 1 is affected indirectly through process interaction due to the nature of process.

Table 4 Summary of controller effectiveness

	undershoot			no offset			overshoot		
	S=2, J=1.5			S=2, J=2			S=2, J=3.5		
Controller type	Offset		Oscillation	Offset		Oscillation	Offset		Oscillation
Output	Output 1	Output 2	Both	Output 1	Output 2	Both	Output 1	Output 2	Both
Normal MPC	-0.0151	-0.0642	YES	-0.0151	-0.0642	YES	-0.0151	-0.0642	YES
Backlash MIQP	1.0357	-2.1763	NO	0.6531	-1.4167	NO	2.1757	-4.4086	NO
Stiction MIQP	0.0115	-0.0118	YES	0.0269	0.0294	YES	-0.0428	-0.0941	YES

Figure 7 shows the undershoot stiction case i.e. slip-jump, J value less than the deadband, S. The standard MPC (denoted as 'nlmpc') brings the process output near to the set point however fails to remove offset and oscillation. MIQP-MPC ('bcklash') removes oscillation completely however does not remove offset. Modified MIQP-MPC ('modified'), which has had the constaraints loosened, reduces the offset but fails to remove oscillations. Since the slip-jump, J is small in stiction undershoot the offset amount is smaller.

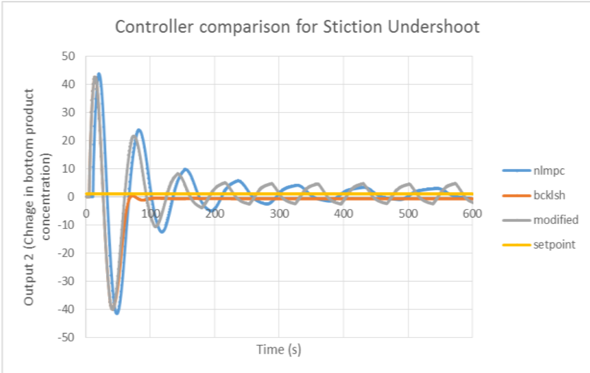


Figure 7 PV for output 2 under stiction undershoot

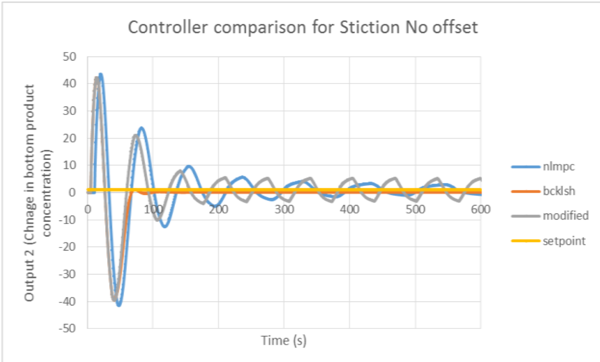


Figure 8 PV for output 2 under stiction no offset

Figure 8 shows the no offset stiction case i.e. slip-jump, J value equal to the deadband, S. The standard MPC ('nlmpc') brings the process output near to the set point however fails to remove offset and oscillation. MIQP-MPC ('bcklash') removes oscillation completely however does not remove offset. Modified MIQP-MPC ('modified') reduces the offset but fails to remove oscillations. Since the slip-jump, J is equal to deadband, S in stiction no offset the offset amount is smallest because the compensation for deadband compensates for slip-jump also.

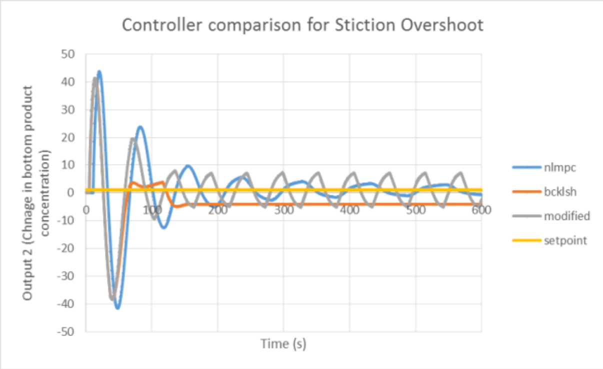


Figure 9 PV for output 2 under stiction overshoot

Figure 9 shows the overshoot stiction case i.e. slip-jump, J value higher than the deadband, S. The normal non-linear MPC ('nlmpc') brings the process output near to the set point however fails to remove offset and oscillation. MIQP-MPC ('bcklash') removes oscillation completely however does not remove offset. Modified MIQP-MPC ('modified') reduces the offset but fails to remove oscillations. Since the slip-jump, J is greater than the deadband, S in stiction overshoot the offset amount is largest because slip-jump introduced offset to the system.

4.0 CONCLUSION

The optimization approach particularly is the ideal strategy for stiction compensation. It reduces the valve stem aggression, reduce the energy added to the compensation signal and reduces the process output variability. MIQP-based optimization formulation is very effective for MPC controllers [7]. The extension of MIQP-based MPC functionality to control valve stiction nonlinearities is very promising.

Modification to the MIQP optimization formulation by loosening constraints resulted in better performance in terms of removing the offset at the expense of introducing oscillations into the system.

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