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Model predictive control design for multivariable processes in the presence of valve stiction☆

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ABSTRACT

This paper presents different formulations of Model Predictive Control (MPC) to handle static friction in control valves for industrial processes. A fully unaware formulation, a stiction embedding structure, and a stiction inversion controller are considered. These controllers are applied to multivariable systems, with linear and nonlinear process dynamics. A semiphysical model is used for valve stiction dynamics and the corresponding inverse model is derived and used within the stiction inversion controller. The two-move stiction compensation method is revised and used as warm-start to build a feasible trajectory for the MPC optimal control problem. Some appropriate choices of objective functions and constraints are used with the aim of improving performance in set-points tracking. The different MPC formulations are reviewed, compared, and tested on several simulation examples. Stiction embedding MPC proves to guarantee good performance in set-points tracking and also stiction compensation, at the expense of a lower robustness with respect to other two formulations.

1. Introduction

Control valves are the most commonly used actuators in the process industries. Unfortunately, in many cases valves not only contain static nonlinearity (e.g. saturation), but also dynamic nonlinearity including backlash, friction, and hysteresis. Deadband due to backlash and mostly static friction (stiction) is a typical root source of the valve problems. A control valve with excessive deadband may not even respond to small changes in control action. As a result, these malfunctions may produce sustained oscillations in process variables, decrease the life of control valves, and generally, lead to inferior quality end-products causing reduced profitability of the whole industrial plant [2]. Hence, it appears that the potential benefits of using advanced control algorithms, as model predictive control (MPC), could be diminished because of poor valves, especially if their faults and malfunctions are not expressly considered in the plant model.

As a matter of fact, MPC has been used as an useful tool to improve control performance in the presence of various types of actuator faults, thus forming effective examples of fault tolerant control (FTC), as in [3,4]. In addition, MPC has been specifically applied as a compensation strategy for several types of control valve malfunctions. In particular, the first MPC-based formulation was developed in [5], using a mixed-integer quadratic programming (MIQP) on constraints of the input. An inverse backlash model and valve saturation are incorporated in the controller to overcome the deadband associated with backlash. Later, this structure has been applied to a system with valve stiction in [6]. Due to the high computational burden and the resulting feedback effect, this approach may be inefficient in the case of severely nonlinear systems (high stiction) or highly dimensional systems. Further investigations of the same method in the case of valve stiction within the process, but not in the model, have been presented in [7].

Rodriguez and Heath [8] have proposed a formulation which reduces the bounds of optimization variables computed by the MPC, by trying to delete different types of valve nonlinearity, and by reducing the problem to a purely linear structure. The controller is indeed in series with a block that applies the inverse model for deadzone, backlash or stiction to the MPC output and sends this signal to the faulty valve, which can eventually saturate. Recently, Durand and Christofides [9] have presented an economic MPC structure which includes a detailed physical stiction model, constraints on the magnitude and rate of change of the input, and is combined with a slave controller of PI-type that regulates the valve output to its MPC set-point. This approach comprises a compensation strategy for nonlinear process systems, which can prevent the MPC from requesting physically unrealistic control actions due

☆ A preliminary version of this paper has been presented in [1].

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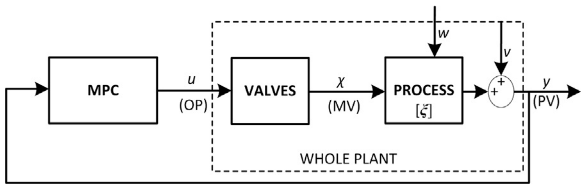

Fig. 1. The closed-loop system with (sticky) control valves followed by the process.

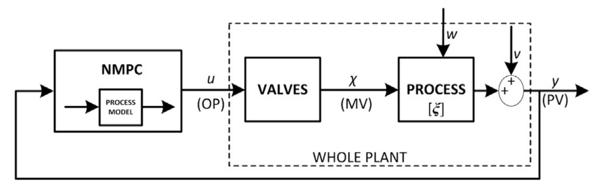

Fig. 2. Closed-loop system with "stiction unaware MPC".

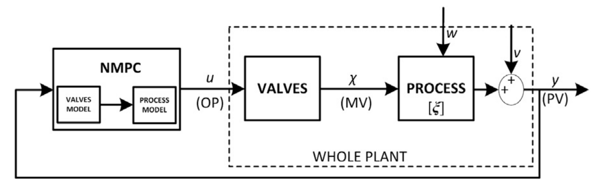

Fig. 3. Closed-loop system with "stiction embedding MPC".

to stiction. Later, the same authors have replaced in [10] the first-principles model for the valve layer with a procedure for developing empirical models based only on data of valve set-point and flow rate. This approach incorporates a logic structure that activates different equations depending on the valve condition (that is, sticking or sliding phase): this forms a piecewise model where set-point changes may set which equations have to be chosen. The empirical model proves to be less stiff than the first-principles model and may improve the computation time with limited violations of process constraints.

As stated before, when stiction is present, the valve is not effective in following the command signal imposed by the controller. As a result, a limit cycle with sustained oscillations is typically produced in the proximity of the steady-state operating points. One way of reducing stiction effects is to explicitly take this malfunction into account in MPC design so that an improved performance could be obtained. As in many other fault tolerant control systems, where the fault estimate is crucial, for a good stiction tolerant MPC, a solid estimate of the stiction amount is needed, and the sticky valve must be properly located, especially when the system is multidimensional. For this purpose, well-established techniques of oscillation detection [11], and stiction diagnosis and quantification [12] could be used and adapted as necessary.

This paper is focused on designing and comparing different strategies of model predictive controller to handle static friction in control valve. Among three main different solutions, one MPC formulation considers valve stiction explicitly, using a semiphysical model [13] which is proved to give very close responses with respect to well-established first-principles models. The objective of this model-based approach is to compensate for the undesired effects of stiction on the controlled systems. Note that no method for valve stiction quantification has been expressly used or derived. Conversely, being stiction quantification beyond the scope of the paper, the amount of stiction is assumed as prior knowledge for predictive controllers.

The various controllers have been previously derived for single-input single-output (SISO) systems with linear process dynamics, as the nonlinearity came only from the valve [1]. In this work, the formulations have been refined and extended to multidimensional processes and nonlinear (and linearized) systems. An appropriate input sequence, derived from the two-move stiction compensation method and used as warm-start for MPC, is developed to improve set-point tracking performance. The considered MPC formulations are analyzed and compared using as test bench several simulation examples.

2. Problem definition

The whole multivariable plant is formed by the control valves followed by the process dynamics as shown in Fig. 1. In detail, χ and y are the process input and output, that is, the valves output and the control variables, respectively; then, u is the MPC output, while w and v are white Gaussian noise.

In [1] the case of SISO system was studied. The system comprised a nonlinearity with memory for the valve followed by a linear dynamics for the process, thus forming an extended Hammerstein structure for the whole plant. In this work, applications to MIMO systems with linear and nonlinear processes are presented.

In particular, the process dynamics is as follows:

$$\begin{aligned} \xi_{k+1} &= f_P(\xi_k, \chi_k) + w_k \\ y_k &= h_P(\xi_k) + v_k \end{aligned} \tag{1}$$

where variables are $\chi \in \mathbb{R}^m$, $u \in \mathbb{R}^m$, $y \in \mathbb{R}^p$, and $\xi \in \mathbb{R}^n$ (the process states), being n the model dimension; while functions are f_P: $\mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}^n$, h_P: $\mathbb{R}^n \to \mathbb{R}^p$. Whereas, the dynamics of the m valves is described by a data-driven stiction model:

$$\chi_k = \varphi(\chi_{k-1}, u_k) \tag{2}$$

expressed by the nonlinear function φ: $\mathbb{R}^m \times \mathbb{R}^m \to \mathbb{R}^m$, which is later discussed. Overall, the output of valve system χ represents the first m components of the state vector of the complete plant: $z_k = [\chi_{k-1}^T, \xi_k^T]^T$, so that $z \in \mathbb{R}^{n_z}$, being $n_z = m + n$. Therefore, the whole dynamics can be written as:

$$\begin{aligned} z_{k+1} = \begin{bmatrix} \chi_k \\ \xi_{k+1} \end{bmatrix} = \phi_P(z_k, u_k) &= \begin{bmatrix} \varphi(\chi_{k-1}, u_k) \\ f_P(\xi_k, \varphi(\chi_{k-1}, u_k)) + w_k \end{bmatrix} \\ y_k &= \zeta_P(z_k) + v_k \end{aligned} \tag{3}$$

where ϕ_P: $\mathbb{R}^{n_z} \times \mathbb{R}^m \to \mathbb{R}^{n_z}$, and ζ_P: $\mathbb{R}^{n_z} \to \mathbb{R}^p$, being $\zeta_P(z_k) = h_P(\xi_k)$. Note that in the present discussion, all actuators are assumed to be control valves, possibly affected by static friction. If some actuators are not valves, suitable simplifications can be easily made.

2.1. Proposed MPC approaches

Three different MPC approaches are presented and compared in this work. The first formulation is a "stiction unaware MPC", with a partial nonlinear formulation since it completely disregards the valves dynamics and uses only the nonlinear process model for the whole plant (see Fig. 2). Secondly, a "stiction embedding MPC" is considered, as shown in Fig. 3. This controller is aware of the stiction presence, as it uses an extended model – comprised of valves and process dynamics – thus forming a full nonlinear formulation.

Finally, the third approach is also aware of stiction, but it has an explicit model for the inverse dynamics of stiction ($\tilde{\varphi}^{-1}$), as in Fig. 4. In this case, $\tilde{u}$ is the MPC output, subject to optimization, which forms input to stiction inverse model, and $u = \tilde{\varphi}^{-1}(\tilde{u})$ is the output of the whole controller. Note that, for a perfect stiction inversion, one get $\varphi(\tilde{\varphi}^{-1}(\tilde{u})) = \tilde{u}$, and then $\tilde{u} \equiv \chi$. This type of formulation, introduced by [8], has the advantage of considering expressly stiction dynamics, but it is mainly beneficial when the controller uses a linear model, that is, it is based on a linearized process dynamics.