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Benefits in using model based predictive control

during drying and lyophilisation

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Introduction

The aim of this paper is to show how model based predictive control (MBPC or MPC) techniques may also be used for drying and lyophilisation processes to improve their efficiency in term of production, like in other industrial application domains. For example, it is well known that drying is a highly energy intensive operation and it represents from 10% to 25% of the national industrial energy in the developed world [1] whereas a majority of industrial dryers operate at low energy efficiency, from a disappointing 10% to 60% (this ratio is defined as the theoretical energy required for the drying to the actual energy consumed). Therefore, due to the escalating energy costs and global competition, these performances have to be improved. This can be done using control tools.

With process control, we mean control methods where the inputs (manipulated variable) of a processing plant are automatically tuned during the production by designed controllers, such that the controlled variable follows the specified production needs. In industrial applications, MPC is one of the most popular controllers since its birth in the 1970s and after the PID (born in the 1940s), MPC has become the second paradigm in control: in 2003, there were more than 4000 industrial applications of MPC [2], especially in refinery and petrochemicals. In the meantime, control tools are not widely applied in drying [3], in spite of some benefits already obtained. For example [4], in a beet sugar factory, a MPC helped to reduce the energy costs by 1.2% (18,900 £/year) and to decrease the downstream energy cost by 14,000 £/year. The product yield increased by 0.86% worth 61,600 £/year and off specification production decreased from 11% to 4%. Finally, the payback time (including hardware and development) was 17 months. In this paper, an example of the use of a MPC is shown for a lyophilisation process during the primary stage of the freeze drying process of a Bovin Serum Albumin (BSA) solution. In a user-friendly code (MPC@CB³), simulation results show here the efficiency of the MPC algorithm, especially in term of robustness with respect to uncertainties in one of the model parameters. The MPC allows the controlled temperature to track a specified time-varying trajectory. Any other constrained optimization problem may be

specified in MPC@CB, based on measured (or estimated) and modeled variables.

Model predictive control features

Model-based predictive control is a particular class of optimal controller. The idea began in the 1960s and a real interest started to emerge in the 1980s after publication of the first papers. Then, new generations of MPC algorithms were formulated (QDMC, GPC, PFC, DMC+ ...). The first main advantage of MPC is that constraints (due to: manipulated variables physical limitations, operating procedures or safety reasons...) may be explicitly specified into this formulation. The second main advantage of MPC is its ability to be used for simple and complex model based processes (time delays, inverse responses, significant non-linearities, multivariable interaction, modeling uncertainties). Many MPC approaches have been proposed along the past three decades, most of them based on a receding-horizon strategy, i.e., at each current sampling instant k the following actions are taken:

- the plant measurements are updated for use in the feedback/feedforward control loop;
- the plant model is used to predict the output response to a hypothetical set of future control sequence;
- a function including the cost of future control actions and future deviations from a reference behaviour is optimized to give the best future control sequence;
- the first movement of the optimal control sequence is applied on the process.

These operations are repeated at time $k+1$. However, if the model exhibits a non-linear behavior, a numerical solution technique must be used to solve this optimal problem. The computational effort varies somewhat because some solution methods require only that a feasible (and not necessarily optimal) solution should be found or that only an improvement should be achieved from time step to time step.

MPC for a lyophilisation process: example

Freeze drying, also called, lyophilisation, is a drying process used in biotechnology, food and pharmaceutical industries

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frequently used to stabilize and preserve the products [5]. Compared with conventional drying techniques, freeze drying is generally considered to produce the dried product with the highest quality. Until now, a larger use of the freeze drying is limited by its cost and its use remains therefore limited for high value added products, like pharmaceutical products. One very important parameter in the study of the freeze drying is the temperature of the product which must be carefully controlled during the primary and the secondary stages of freeze drying. Generally, dynamic models for freeze-drying predict drying behaviors more accurately than steady models. As a counterpart, complex transport equations are required, which are difficult to solve and are based on variables and parameters difficult to measure accurately experimentally. Dynamics model are preferred for model based control.

An example of MPC in lyophilisation is discussed here: the controlled temperature has to track as best as possible the specified time-varying reference trajectory during the primary stage of the freeze drying process of a Bovin Serum Albumin (BSA) solution. To satisfy this objective, a mathematical model, that can predict the behavior of the freeze drying process, is used [6]. During the primary drying, the product is composed of two phases: a dry layer, in which the majority of water is sublimated and a frozen layer. These two areas are separated by a moving interface called the sublimation ice front described by the space coordinate z at $z=H(t)$. This complex model has already been used in our predictive control software (MPC@CB) to tune online the shelve temperatures according to the control objective [7]. In term of uncertainties, [8] shown that the heat capacity in the frozen layer Cp_2 is known with relatively large errors (up to 24%). The idea is to show here how the MPC is able to control online the primary stage drying to a desired behavior, in spite of this parameter uncertainty.

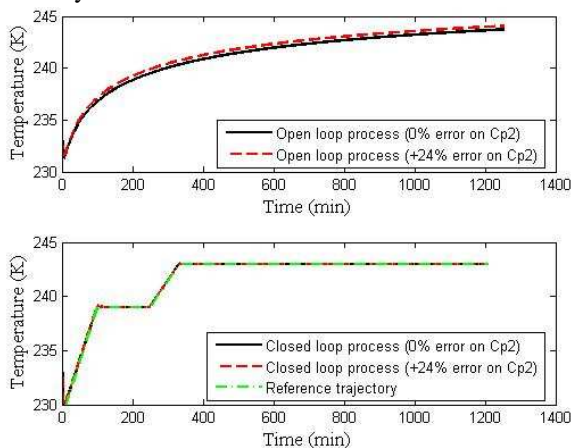


Fig. 1: Controlled temperature in: open loop control (top), MPC control (bottom). No error (cont.) and with modeling error (dash). In closed loop, reference trajectory (dash dot).

Top of Fig. 1 shows that, with the same constant open loop control conditions, the measured temperature is different for 2 runs with different values for Cp_2 . In the meantime, the position of the sublimation front also differs (top of Fig. 2). If the (closed-loop) MPC is employed in order to track a specified temperature trajectory, the measured temperature is almost the same for 2 runs with different values for Cp_2 (bottom of Fig. 1): this is a robustness property of this controller. In the meantime, the position of the sublimation front is almost the same in both cases (bottom of Fig. 2).

MPC is therefore of interest to control such processes featuring parameter uncertainties.

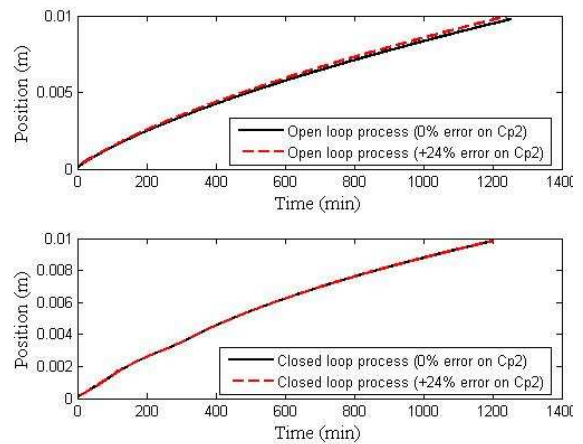


Fig. 2: Sublimation front position in: open loop control (top), MPC (closed loop) control (bottom). No modeling error case (cont.) and modeling error case (dash).

Conclusion

Since 1998 [3], the yearly mean publication rate of papers using a first principle model for control has been multiplied by 11! This increase is quiet similar to the increase of the control papers in drying based on optimal control strategies, like MPC. With 60 000 products dried and 100 dryer types used worldwide [1], a real potential exists. With control tools like MPC, it is expected that the industrial drying operation will continue to improve its energy efficiency while enhancing product quality and reducing the negative environmental impact of dryers.

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