Journal of Process Control 24 (2014) 296–303

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Model Predictive Control in Pulsed Electrochemical Machining

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A R T I C L E I N F O

Article history:
Received 15 July 2013
Received in revised form 7 October 2013
Accepted 1 November 2013
Available online 9 January 2014

Keywords:
Model Predictive Control
Electrochemical Machining
Linear Time Variant MPC
I/O-Linearization

A B S T R A C T

In this work a Model Predictive Control (MPC) approach is used for controlling a Pulsed Electrochemical Machining (PECM) process. The MPC problem is formulated in order to optimally reach a desired state while satisfying various restrictions. PECM is modeled as a constrained nonlinear system. In the first approach the system is input-output linearized and a linear MPC scheme is applied to control it. In comparison a second approach uses the linearization around the current working point resulting in a Linear Time Variant system. This linear system is controlled using Linear Time Variant MPC (LTV-MPC). The simulation results are compared and the most promising controller is implemented on a real time platform controlling a PECM plant. The experimental results with online parameter estimation are shown and discussed.

1. Introduction

Electrochemical Machining (ECM) is a non-conventional way to process hard metals. This technique is based on electrolysis. A negatively polarized metallic cathode, the tool electrode, is advanced towards a metallic anode, the work piece. A DC voltage is applied across the working gap which is filled with an appropriate electrolyte like sodium nitrate. According to Faraday's law, material from the work piece is dissolved proportional to the resulting current. Due to the fact that most of the material is dissolved where the inter-electrode gap is smallest, the work piece is shaped according to the negative of the tool electrode. The pressurized electrolyte is pumped through the inter-electrode gap in order to prevent boiling and to sweep away the products of the electrode reactions.

Pulsed Electrochemical Machining (PECM) is an advanced technique applying a pulsed DC voltage across the working gap. For enhanced support of cleanliness of the electrolyte, the tool electrode is retracted during the pulse pause. In this way the linear motion of the advancing tool electrode is superimposed with an oscillatory motion of a given frequency.

The inter-electrode gap and the current density are the most important quantities for the PECM process. The current density specifies the speed of the dissolution and has a high influence on the surface roughness. A constant gap size ensures process stability and prevents shortcuts which would lead to the destruction of the work piece. The gap size cannot be measured directly during the machining process and thus has to be determined with an observer. In [1] an observer, with a structure similar to a Luenberger observer, together with a Two-Degree-of-Freedom controller was presented for the single-sided PECM process. For the single-sided ECM process other approaches using neural networks [2], fuzzy-logic control [3] or basic PID controllers [4] can be found in the literature.

PECM is a multivariable process, exhibiting slow dynamics and being constrained by various restrictions. This makes Model Predictive Control (MPC) a perfectly suitable control scheme, which is well established in the process industry [6,7], especially for chemical and petrochemical plants, for many years. It is an effective tool to deal with multivariable constrained control problems [8,9]. However, to the authors knowledge, MPC has not yet been used to control the PECM process, especially two-sided PECM, which is discussed in this work.

The biggest drawback in MPC is its computational complexity. For nonlinear systems a nonlinear optimal control problem has to be solved. The PECM process is described by a nonlinear system but the MPC scheme used to control it should be implemented on a real time platform with limited processing power. Therefore the model is linearized. The resulting linear optimal control problem can easily be solved by a quadratic program (QP). In the following, two different methods for linearization of the model are used. In Section 3.1 Input-Output Linearization [5] is applied and in Section 3.2 the model is linearized around the current working point. For both methods a linear MPC controller is derived.

The rest of this paper is organized as follows: Section 2 starts with the modeling of the PECM system and all important constraints. In Section 4 the performance of the two MPC controllers are compared in simulations. The more promising approach is implemented on a real time platform and experimental results are shown in Section 5.

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http://dx.doi.org/10.1016/j.jprocont.2013.11.003

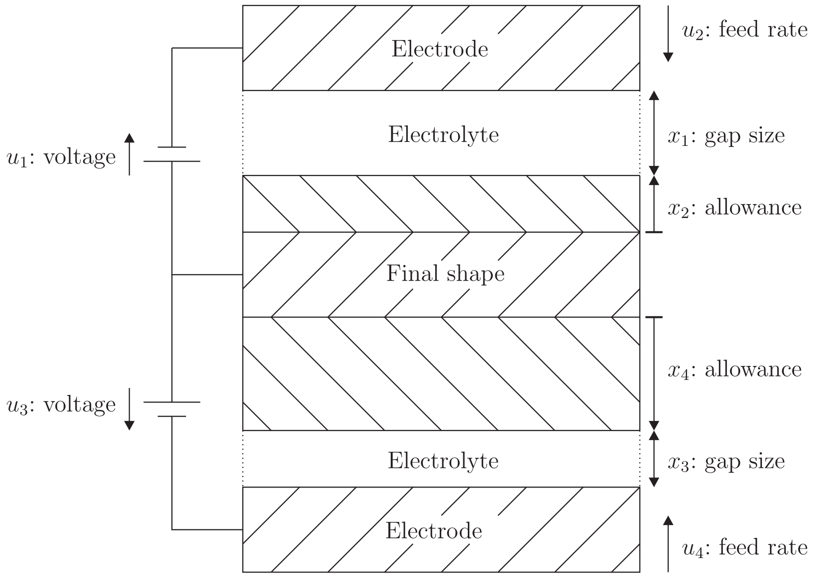

Fig. 1. Process illustration.

2. System and constraint modeling

Before the MPC controllers are discussed, the modeling of the PECM process is reviewed. Further details on PECM modeling can be found in [10,11].

2.1. System modeling

For many industrial applications flat-end or close to flat-end tool electrodes are used. Those electrodes with constant area A are advanced with the user-defined feed rate f towards the work piece. The working gap of size s is filled with an electrolyte with conductivity κ. Using an electric equivalent circuit, the working gap can be modeled as a gap size dependent resistor. In PECM the applied voltage U has to exceed the overpotential ΔU before any current flow can be observed. There is also another ohmic potential drop at the electrode-electrolyte interface which is modeled by the resistance R. Using this equivalent circuit the current across the gap is

$$I = \frac{U - \Delta U}{R + s/(\kappa A)}. \tag{1}$$

According to Faraday's law the volume of the dissolved material is proportional to the current flow. The change in the gap size can therefore be described as the difference between the dissolved material and the tool feed rate

$$\dot{s} = k_d \frac{U - \Delta U}{R + s/(\kappa A)} - f. \tag{2}$$

It should be noted that many properties of the dissolution process are incorporated in the constant k_d. For example the valency of the machined alloy, the dissolution efficiency reasoning from side reactions or pulse on/off ratio.

To describe the machining allowance a only the dissolution effect has to be considered. Starting from a non-zero value the machining has to be stopped when the allowance reaches zero. The corresponding differential equation is

$$\dot{a} = -k_d \frac{U - \Delta U}{R + s/(\kappa A)}. \tag{3}$$

This system state is particularly important when the work piece is machined from two sides. Because then the controller has to make sure that at the end of the machining time both allowances have reached its zero value. Therefore one of the system outputs in two-sided machining is chosen as the difference between the two allowances. The other outputs $\mathbf{y} \in \mathbb{R}^5$ of the two-sided system are the current on each side and the corresponding gap size. Using $\mathbf{x} \in \mathbb{R}^4$ as the system state and $\mathbf{u} \in \mathbb{R}^4$ as the input, the complete system description is

$$\begin{aligned}
\dot{x}_1 &= k_d \frac{u_1 - \Delta U}{R + x_1/(\kappa A)} - u_2 & y_1 &= x_1 \\
\dot{x}_2 &= -k_d \frac{u_2 - \Delta U}{R + x_2/(\kappa A)} & y_2 &= \frac{u_2 - \Delta U}{R + x_2/(\kappa A)} \\
& & y_3 &= x_3 \\
\dot{x}_3 &= k_d \frac{u_3 - \Delta U}{R + x_3/(\kappa A)} - u_4 & y_4 &= \frac{u_4 - \Delta U}{R + x_4/(\kappa A)} \\
\dot{x}_4 &= -k_d \frac{u_4 - \Delta U}{R + x_4/(\kappa A)} & y_5 &= x_2 - x_4.
\end{aligned} \tag{4}$$

An illustration of the process and its input and state variables is shown in Fig. 1 and an overview of all system variables and their physical meaning is shown in Table 1.

Note that the allowance cannot be measured directly, but can be reconstructed by subtracting the estimated gap size from the measured electrode position.

2.2. Constraint modeling

The system underlies various restrictions on the actuators. The power supply source can only provide positive voltage up to $u_{\max}$. The lower limit is described by ΔU which is the minimum voltage before any current flow can be observed. The feed rate can be limited as well, the test rig allows only positive feed rate values during machining. Rate of change constraints are not considered.

Table 1
List of system variables and their physical meaning.

Variable	Meaning
u_1, u_3	System input: applied voltage
u_2, u_4	System input: feed rate
x_1, x_3	System state: gap size
x_2, x_4	System state: allowance
y_1, y_3	System output: gap size
y_2, y_4	System output: current
y_5	System output: allowance difference