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Linear algebra based controller design applied to a bench-scale oenological alcoholic fermentation

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A B S T R A C T

This work presents a controller design for a non-isothermal alcoholic fermentation to produce wines in a bench-scale bioreactor. The main controller objective is that the system tracks an optimal operation trajectory to produce wines with constant quality. This trajectory is previously determined for the biomass and for the CO_2 produced by the fermentation. To meet the goal, the process is approximated using numerical methods, and then, the problem is posed like solving a system of linear equations. The necessary conditions for the system of linear equations has exact solution are analyzed. Afterwards the control action is obtained by solving the system of linear equations. The methodology success is shown using experimental results.

1. Introduction

A bioprocess is a method or operation of preparing a biological material, especially a product of genetic engineering, for commercial use. Generally include one or more bioreactors, also named fermenters in the wine industry. Because of complex nature of microorganism growth and product formation in batch and fed-batch cultures, which are often employed in preference to continuous cultures, the control of bioprocesses continues to be a challenge to chemical engineers (Komives & Parker, 2003).

During fermentation, the microbial or enzymatic agents are grown in a controlled mode and the feedstock is converted or transformed through biochemical reactions (Valencia Peroni, 2003). From the point of view of cell growth as a result of the utilization of nutrients, microbial biomass increases over time.

One of the main problems in non-linear control systems is the trajectory tracking. In general, the objective is to compute the control actions so that the system tracks a previously established trajectory. Li and Wozny (2001) considered the trajectory tracking problem for multiple-fraction batch distillation. Since the latter system is non-linear and time dependent, the objective cannot be achieved with a conventional proportional integral derivative (PID) controller, the use of more advanced controllers is necessary. Golshan, MacGregor, Bruwer, and Mhaskar (2010) considered an alternative model predictive control for trajectory tracking based on latent variable models; such algorithms were applied to a batch reactor with an exothermic reaction. Moreover, controllers based on neural networks have been used in trajectory tracking problems (Horn, 2001; Sjoberg & Agarwal, 2002). Horn (2001), used input–output linearization via states feedback and applied that technique for trajectory tracking on a batch polymerization reactor. Sjoberg and Agarwal (2002) applied the same strategy on an exothermic batch reactor, as well. Tebbani, Dumur, and Hafidi (2008), determined first, the optimal trajectory of a fed-batch bioreactor, and the optimal trajectory tracking was then performed thanks to cascaded control architecture. This latter has an inner loop consisting of a linearizing state-feedback control law, and an outer one including a proportional integral (P.I.) controller, in order to cancel steady tracking errors. Cédric, Michel, Lionel, Brigitte, and Chabriat (2011) presents an observer coupled to a multivariable set-point tracking control, based on an input–output linearization algorithm.

Main operation variables in fermentations are: pH, temperature, dissolved oxygen concentration, agitation speed, foam level, and others (Morari & Zafiriou, 1997). For example, temperature is seen as a fine tool for better regulation of the fermentation progress, in accordance with a winemaking strategy depending on the desired wine (Torija et al., 2003; Molina, Swiegers, Varela, Pretorius, & Agosin, 2007; Romero Cascales, 2008). With on-line monitoring of the fermentation rate, winemaking operations

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(temperature regulation, nutrient additions, pumping, etc.) can be adapted to actual fermentation behavior. Some studies suggest that controlling the fermentation rate may be at least as important as controlling the temperature; one of them highlights the benefits of controlling CO_2 production rate (Sablayrolles, 2009). Additionally, fermentation presents important interactions between cell bio-kinetics and the bioreactor hydrodynamic conditions, which lead to models with non-linear and unsteady characteristics. Therefore, advanced optimization and control tools for monitoring and controlling strictly the process, are required. The implementation of advanced control strategies needs appropriate dynamic models and reliable on-line measurements (Henson, 2003). Furthermore, alcoholic fermentation models can assure wine quality and reproducibility among batches (Zenteno, Pérez-Correa, Gelmi, & Agosin, 2010), as well. Moreover, non-isothermal models developed from laboratory or bench-scale alcoholic fermentations have been validated or tested with good performance, or highlighted their possible scaling-up to industrial tanks (Phisalaphong, Srirattana, & Tanthapanichakoon, 2006; Colombié, Malherbe, & Sablayrolles, 2007; Malherbe, Fromion, Hilgert, & Sablayrolles, 2004; Coleman, Fish, & Block, 2007). Casalta et al. (2010) have carried out a comparison of laboratory and pilot-scale fermentations in winemaking conditions by means of the study of kinetics and the production of aromatic compounds of own and other authors′ experiments as the latter mentioned. Authors′ contributions on modeling and advanced controlling of oenological alcoholic fermentations are: an advanced temperature control system based on an improved non-isothermal phenomenological model that allows tracking complex temperature profiles to achieve optimal quality of wine (Ortiz, Vallejo, Scaglia, Mengual, & Aballay, 2009), and the design of a controller based on numerical methods applied to a bench-scale bioprocess for good-quality wines (Scaglia, Rosales, Quintero, Mut, & Agarwal, 2010b).

From a mathematical point of view, models must be at the same time accurate and simple to be used in on-line control algorithms. In previous contributions, the authors have addressed isothermal and non-isothermal first principles and hybrid neural models, and an improved isothermal phenomenological model with satisfactory capability to approximate the main variables profiles of oenological alcoholic fermentations (Vallejo et al., 2005; Ortiz, Aballay, & Vallejo, 2006; Aballay, Scaglia, Vallejo, & Ortiz, 2008; Scaglia, Quintero, Mut, & di Sciascio, 2009b). Also, the improved phenomenological model has been extended to a non-isothermal operation (Aballay, Scaglia, Vallejo, Rodríguez, & Ortiz, 2010).

The oenological alcoholic fermentation control is carried out, mostly, by means of temperature manipulation, thus, cells population and main fermentation variables are regulated. The desired organoleptic wine properties can be obtained in this fashion, which depend on population of the proper selected yeast as well as its variation in time. Cells as living beings evolve as such and have precise needs of nutrition and the medium they live into. Yeasts are sensitive to temperature, and concentrations of oxygen, sugars, minerals and nitrogen-based substances. It is usual that by using the same varietal must (grape juice) and composition, pure yeast starter culture, initial conditions and constant temperature to carry out an oenological alcoholic fermentation, the cells population evolution in time has not the same performance among batches, which affects the final wine quality (Pretorius, 2000; Torija et al., 2003). This is the reason why fermentation reproducibility among batches is a current trouble.

In this work, an advanced trajectory tracking control for an oenological alcoholic fermentation operated on batch mode is presented. The complex dynamics, nonlinearity and non-stationary of fermentation make the control of this bioprocess, is a difficult task. Thus, the main control objective was that the key process variables evolve in time tracking an optimal trajectory previously defined. More specifically, the given trajectories were the main process state variables, as viable cells concentration and CO_2 released, from which a suitable temperature profile for desire fermentation evolution was determined to assure fermentation reproducibility and the wine quality. This simple approach suggests that knowing the desired state value, a value for the required control action can be found; that force the system to move from its current state to the desired one. The developed controller for tracking the optimal trajectory in some states was based on determining the desired trajectories of the other state variables. Such states were determined by analyzing the necessary conditions so that the linear equations system had exact solution. Then, the control signals were obtained by solving the system of linear equations. Furthermore, variables transformations in the controller design were not necessary either. This technique for controllers design for trajectory tracking has been applied to non-linear multivariable systems as shown in Scaglia, Aballay, Vallejo, Suarez, and Ortiz (2010a), Scaglia, Aballay, Mengual, Vallejo, and Ortiz (2009a), Rosales, Scaglia, Mut, and di Sciascio (2009), and a complex system consisting of a set of nonlinear multivariable systems that must work in a cooperative manner (Rosales, Scaglia, Mut, and di Sciascio, 2011).

The work is organized as follows. Section 2 presents a brief description of fermentation in winemaking and its modeling. Also, the used non-isothermal model with considerations on its components and parameters, as well as, on main properties, is described in this section. In Section 3, details about the controller design are depicted. Experimental results showing the accomplishment of the proposed controller are illustrated in Section 4. Finally, Section 5 presents the discussion regarding major obtained results, and analyzes the contribution of the work and outlines some topics to be addressed in future works.

2. Process model

The reductive metabolic pathway characterizes the yeast population growth in anaerobic conditions. This behavior can be represented as:

$$S \underset{\rightarrow}{\text{yields}} \ Y_{X/S}X + Y_{CO_2/S}CO_2 + Y_{Eth/S}Eth$$

In this equation, X, S, CO_2 and Eth correspond to viable cells, carbon source (glucose and fructose), carbon dioxide and ethanol concentrations (kg m^{-3}), respectively. Whereas, $y_{x/s}$, $y_{CO_2/s}$ and $y_{Eth/s}$ are stoichiometric coefficients. In Eq. (1), only the most abundant products are stated. During grape must fermentation, a number of other minor, but important metabolites are produced (glycerol, higher alcohols, esters, etc.). These by-products are related with sensory attributes of wine. According to Coleman et al. (2007), model′s prediction capabilities of sugar and ethanol are important from an enologist′s point of view, due to they are the most important state variables.

Remark 1. In this paper the concept of cells, biomass and yeast are used in an equivalent way.

The ethanol production reaction from glucose is the following:

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 \quad (1)$$

Metabolite accumulation in the extra-cellular medium has been modelled by a set of ordinary differential equations (ODE) based on the mass balances on cells, substrate as carbon source and ethanol. Released carbon dioxide is also included in the model because such variable provides an inexpensive and convenient way to monitor the evolution of the other process variables, especially those stoichiometrically related. Model assumptions were: balance parameters of the model, including pH, were stated