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A reduced order soft sensor approach and its application to a continuous digester

Hector J. Galicia[a], Q. Peter He[b,*], Jin Wang[a,**]

[a] Department of Chemical Engineering, Auburn University, Auburn, AL 36849, USA
[b] Department of Chemical Engineering, Tuskegee University, Tuskegee, AL 36088, USA

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ABSTRACT

In many industrial processes, the primary product variable(s) are not measured online but are required for feedback control. To address this challenge, there has been increased interest toward developing data-driven soft sensors using secondary measurements based on multivariate regression techniques. Among different data-driven approaches, the dynamic partial least squares (DPLS) soft sensor approach has been applied to several industrial processes. However, despite its successful applications, there is a lack of theoretical understanding on the properties of the DPLS soft sensor. Specifically, whether it can adequately capture process dynamics and whether it can provide unbiased estimate under closed-loop operation have not been examined rigorously. In this work, we provide a theoretical analysis to answer these questions. In addition, we propose a reduced-order DPLS (RO-DPLS) soft sensor approach to address the limitation of the traditional DPLS soft sensor when applied to model processes with large transport delay, *i.e.*, large number of lagged variables are required to be include in the regressor matrix in order to capture process dynamics adequately. Compared to the traditional DPLS soft sensor, the proposed RO-DPLS approach not only reduces model size and improves prediction but also provides multiple-step-ahead prediction. The performance of the proposed RO-DPLS is demonstrated using both a simulated single-vessel digester and an industrial Kamyr digester.

1. Introduction

Pulping process, which converts wood chips into pulp by displacing lignin from cellulose fibers, is one of the most important operations in a pulp and paper mill [1]. Yearly US wood pulp production is around 52 million tons and the pulp and paper industry is an important sector of the US manufacturing [2,3]. Kraft pulping is the most commonly used chemical pulping process, which usually utilizes a continuous Kamyr digester. A Kamyr digester is a complex vertical plug flow reactor where the wood chips react with an aqueous solution of sodium hydroxide and sodium sulfide, also known as white liquor, at elevated temperatures. Fig. 1 shows the schematic diagram of a single-vessel Kamyr digester with three distinct zones. Pre-steamed wood chips and white liquor enter the impregnation zone from the top of the digester, and chemicals in white liquor diffuse into the pores of the wood chips in this zone. Subsequently in cook zone the temperature is raised through the upper and lower heated circulation and most of the delignification reactions occur in the cook zone. Finally in wash zone the countercurrent flow of dilute wash liquor quenches the reactions and removes the unreacted chemicals.

It is well known that the performance of the pulping process is of paramount importance to maximize the pulp quality and yield, reduce the overall operating cost including energy usage, and minimize the adverse environmental impacts of pulp mills [1]. The most important quality variable in pulping process is the Kappa number, which represents the residual lignin content of the pulp [1]. It is desired to minimize the variations of the Kappa number in the pulp product. For a continuous digester, process variables are measured at different frequencies. Primary measurement, *i.e.*, the pulp Kappa number, is measured at a low frequency (*e.g.*, one sample every 2 h with 30 min measurement delay); while secondary measurements are measured at a higher frequency (*e.g.*, one per 6–10 min) which include white liquor flow rate, wood chip flow rate, the temperature and composition of upper circulation, lower circulation and extraction [4]. In order to describe the dynamics of a continuous digester and develop effective control methods, first principles or physical models have been developed to simulate the pulping process by approximating the digester with a series of continuous stirred tank reactors (CSTRs) [5,6]. However, control of a continuous digester is challenging due to the following characteristics of the pulping process: (1) long resi-

* Corresponding author.
** Corresponding author.
E-mail addresses: hjg0002@auburn.edu (H.J. Galicia), qhe@tuskegee.edu (Q.P. He), wang@auburn.edu (J. Wang).

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