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IDENTIFICATION OF DYNAMIC CHARACTERIZATION PARAMETERS OF AGITATED PULP CHESTS USING HYBRID GENETIC ALGORITHM

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Pulp suspensions are non-Newtonian and possess a significant yield stress, which creates considerable deviations from ideal mixing as demonstrated by dynamic tests made on both industrial and scale-model pulp chests. Due to the existence of non-ideal flows in agitated pulp chests, the determination of their discrete-time characterization parameters is very challenging. This paper optimally determines these parameters using a multi-parameter hybrid genetic algorithm specially developed to generate robust and high quality results. The algorithm integrates the genetic operations of selection, crossover and mutation with gradient search inside successively expanding and contracting parameter domains using alternating logarithmic and linear mappings. The algorithm is successfully tested on three different sets of simulated data, and it is found to retrieve the model parameters with high accuracy. Three sets of experimental data are then processed by the algorithm for the optimal determination of their characterization parameters. The corresponding optimal outputs match well with their experimental counterparts. The results indicate the potential application of the algorithm to solve non-linear process optimization problems with high accuracies.

Keywords: mixing; pulp chests; multi-parameter optimization; hybrid genetic algorithm; system identification.

INTRODUCTION

Mixing and agitation influence all areas of pulp and paper manufacture. For stock blending, consistency control, bleaching, chemical generation and deinking, effective mixing is vital to successful process results. Agitated pulp chests perform a number of mixing functions. In papermaking, the chests are used to mix two or more pulp streams, often with wet-end chemicals, dyes, fillers, or additives as well as to provide a uniform feed of stock to the paper machine. In pulping processes, the chests are used to ensure uniform flow ahead of many operations including chemical addition in bleaching stages, washers, screens and cleaners. In essence, pulp chests act as low-pass filters attenuating high-frequency variability, and thus compliment the action of control loops, which only attenuate slow disturbances (Bialkowski, 1990).

Agitated pulp chests are often designed based on proprietary experiential information. One common design method has been summarized by Yackel (1990), and is based on matching the momentum flux generated by an impeller with that required to achieve smooth surface motion in the vessel. Ein-Mozaffari *et al*. (2003a) have showed that even when completely smooth surface motion is attained, considerable stagnant regions exist in the chests below the suspension surface. They have found that the power and impeller momentum flux requirements for creating complete motion in the chest are underpredicted by Yackel's method. Furthermore, the power required to eliminate the stagnant regions is at least three times greater than that calculated using that method.

Pulp chests are often designed assuming they are ideally mixed, with the dynamics represented by a first order transfer function and the chest volume selected based on the total residence time required (Brown, 1968; Reynolds *et al.*, 1964; Walker and Cholette, 1958). The complex rheology of a pulp suspension, which is non-Newtonian and displays a significant yield stress (Bennington *et al.*, 1990; Gullichsen and Harkonen, 1981; Wikstrom and Rasmuson, 1998), can create considerable deviations from ideal mixing as shown by dynamic tests made on both industrial and scale-model chests (Ein-Mozaffari *et al.*, 2003b, 2004a, b, 2005). The identified non-ideal flows are short-circuiting (where a portion of the feed directly flows to the exit without entering the mixing zone), recirculation (where a portion of the stock recirculates within the mixing zone), and dead zones (where pulp is stagnant or flows significantly slower than the bulk of the suspension).

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These non-ideal flows reduce the degree of upset attenuation produced by the chest (Ein-Mozaffari *et al.*, 2003b, 2004b, 2005). Typical disturbances occur at frequencies higher than the cut-off frequencies of paper machine control loops. Consequently, the disturbances are not fully attenuated and pass through to the process where they affect paper quality and machine runnability. These effects can be overcome by studying the dynamic behavior of pulp mixing under realistic conditions, and improving the process design accordingly.

Although the identification of continuous-time models has received considerable attention in the past (Johansson, 1994; Johansson *et al.*, 1999; Soderstrom *et al.*, 1997; Whitfield and Messali, 1987), the existence of integer time delays in the pulp chest model makes its identification difficult. Recent developments for the identification of systems with time delays have been reported (Sung and Lee, 2001; Wang *et al.*, 2001) but these schemes are not generic enough to handle this dynamic model. Kammer *et al.* (2005) developed a numerical method for estimating model parameters in the model developed by Ein-Mozaffari *et al.* (2003b). In this method, the estimation of the time delays was performed independently from the estimation of the remaining parameters of the model. The authors proposed two distinct stages for the identification: an efficient but less accurate search for the optimal delays, followed by an accurate search for the whole set of parameters. Although this mechanism is not guaranteed to converge to the global minimum, a Monte Carlo simulation showed very encouraging results.

In the present study, the optimal parameters of the pulp chest model are determined using a hybrid multi-parameter optimization algorithm that is developed by uniquely integrating genetic algorithms (Holland, 1975) with gradient search. The optimization algorithm carries out gradient search as well as the genetic operations of selection, crossover and mutation on binary-coded optimization parameters within their size varying domains using alternating linear and logarithmic mappings. This interaction between genetic operations and gradient search is unique, and leads to efficient search and refinement of optimization parameters. To test and use the algorithm, simulated as well as experimental plant data are employed in conjunction with the following dynamic model, which is non-linear as well as discontinuous. The algorithm identifies the optimization parameters with high accuracies, and can be used to identify non-ideal flows in reactors, packed columns, and heat exchangers; and other processes with internal recirculation such as the physiological system of neuromuscular reflex (Khoo, 2000).

MATHEMATICAL MODEL

Dynamic tests carried out on industrial and scale-model chests have shown that non-ideal flows including short-circuiting, recirculation, and dead zones are common; and significantly reduce the ability of the chest to attenuate fluctuations (Ein-Mozaffari, 2002; Ein-Mozaffari *et al.*, 2004a, 2005). The model developed by Ein-Mozaffari *et al.* (2003b) describes the dynamic non-ideal flow behaviour observed in the industrial and scale-model agitated pulp chests allowing for two parallel suspension flow paths through the mixing chest: (1) a mixing zone consisting of a first order transfer function with delay and feedback for recirculation, and (2) a short-circuiting zone consisting of a first order transfer function plus delay. The combined transfer function for the chest in the continuous-time domain is as follows:

$$G(s) = \frac{fe^{-T_1 s}}{1+\tau_1 s} + (1-f)(1-R)\frac{e^{-T_2 s}}{1+\tau_2 s} \times \left(1 - \frac{Re^{T_2 s}}{1+\tau_2 s}\right)^{-1} \quad (1)$$

In equation (1), f is the fraction of incoming suspension short-circuiting the mixing zone, R is the fraction of pulp recirculated within the mixing zone, T_1 and T_2 are the time delays, and τ_1 and τ_2 are the time constants for the short-circuiting and mixing zones, respectively. Further details are provided in Ein-Mozaffari (2002) and Ein-Mozaffari *et al.* (2003b, 2004b).

Since the data are measured at fixed time intervals, the zero-order hold may be applied to the output signal to transform the above transfer function into the following discrete-time equivalent (Kammer *et al.*, 2005):

$$G(q^{-1}) = \frac{\begin{pmatrix} \rho_1 q^{-d_1} + \rho_2 q^{-(d_1+1)} + \rho_3 q^{-d_2} \\ +\rho_4 q^{-(d_2+1)} + \rho_5 q^{-(d_1+d_2)} \end{pmatrix}}{1 + \rho_6 q^{-1} + \rho_7 q^{-2} + \rho_8 q^{-d_2} + \rho_9 q^{-(d_2+1)}} \quad (2)$$

In equation (2),

$$d_i = 1 + \frac{T_i}{t_s}, \quad i = 1, 2, \qquad d_1 \leq d_2 \quad (3)$$

$$\rho_1 = f(1-a_1), \qquad \rho_2 = -a_2\rho_1 \quad (4)$$

$$\rho_3 = (1-f)(1-R)(1-a_2), \quad \rho_4 = -a_1\rho_3 \quad (5)$$

$$\rho_5 = -fR(1-a_1)(1-a_2), \qquad \rho_6 = -a_1 - a_2 \quad (6)$$

$$\rho_7 = a_1 a_2, \qquad \rho_8 = -R(1-a_2) \quad (7)$$

$$\rho_9 = -a_1\rho_8, \qquad a_i = e^{-t_s/\tau_i}, \quad i = 1, 2 \quad (8)$$

with t_s and q^{-1} respectively as sampling time and backward shift operator. It is assumed that the time delays are multiples of sampling time. The output signal (y) is related to the input signal (u) as follows:

$$y = G(q^{-1})u \quad (9)$$

Equation (9) can be further expressed in terms of the following set of equations:

$$y_i = \begin{cases} y_{\exp,0} = u_0, \quad i \leq 0 \\ (-\rho_6 y_{i-1} - \rho_7 y_{i-2} - \rho_8 y_{i-d_2} - \rho_9 y_{i-d_2-1} \\ \quad +\rho_1 u_{i-d_1} + \rho_2 u_{i-d_1-1} + \rho_3 u_{i-d_2} + \rho_4 u_{i-d_2-1} \\ \quad +\rho_5 u_{i-d_1-d_2}), \quad i = 1, 2, \ldots, N_s - 1 \end{cases}$$
$$u_i = u_0, \quad i \leq 0 \quad (10)$$

where N_s is the number of equispaced samples, and $y_{\exp,0}$ and u_0 are the initial steady state values of y and u.