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Control of a grinding mill circuit using fractional order controllers

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ABSTRACT

This paper presents the design and application of fractional single-input–single-output (SISO) controllers to a grinding mill circuit, which is a multiple-input–multiple-output (MIMO) process. Two kinds of controllers are presented: fractional order proportional-integral (FOPI) controllers, and a combination of FOPI and fractional order model reference adaptive controllers (FOMRAC). The parameters of the controller are tuned using off-line particle swarm optimization. In the presence of disturbances and process noise, the SISO fractional controllers achieve similar or better performance compared to linear model predictive control (LMPC).

1. Introduction

Grinding mill circuits are difficult nonlinear processes to control because of the coupling and interaction between process variables. In general, multivariate control techniques are used to solve this issue, such as model predictive control (MPC), [1–6], inverse Nyquist array [7], extended horizon [8,9], pole placement [8,9], multivariate model reference adaptive control [8,9], direct Nyquist array [8,9], sequential loop closing [8,9], and predictive multivariate neural control [10]. These multivariate techniques can significantly improve process performance compared to decentralized SISO controllers [4,11]. However, because of the ease of implementation of SISO techniques in terms of tuning and maintenance, SISO control techniques remain most prevalent in industrial grinding mill circuits [12].

A great percentage of industries still use proportional integral and derivative (PID) controllers (or only PIs) in their milling circuits, usually because of the difficulty of implementing and maintaining advanced process control, and also because there is a lack of sufficient dynamic and fundamental models for mineral processing circuits [13]. On the other hand, PID controllers are simple, relatively easy to tune and can handle many operating conditions relatively well. However, PID controllers usually cannot handle parameter variations, disturbances and noise in a robust manner, compared to multivariable techniques. Thus, obtaining improvements in the behavior of milling circuits under these operating conditions, using SISO controllers, could be a great intermediate step for industries where the implementation of advanced multivariable control strategies is difficult.

The control of grinding processes is further complicated by the presence of unmodeled process dynamics, time-varying parameters, large time delays, and noisy measurements. These issues, which are impediments for any control technique, are managed through adaptations in the control techniques [8,9,14–19] to improve the grinding circuit's performance.

It has been reported in some works that the use of fractional operators [20] as part of control strategies can improve system robustness in the presence of disturbances, noisy environments, and time-varying parameters. It has been also reported in Aguila-Camacho and Duarte-Mermoud [21] that their use can improve the management of the control energy. Why these advantages are achievable is a research topic currently under investigation, but it seems that the implicit memory incorporated in the definitions of fractional integral and fractional derivative [20] is the key to answer this question. Several control techniques have been generalized with the use of fractional operators: fractional order

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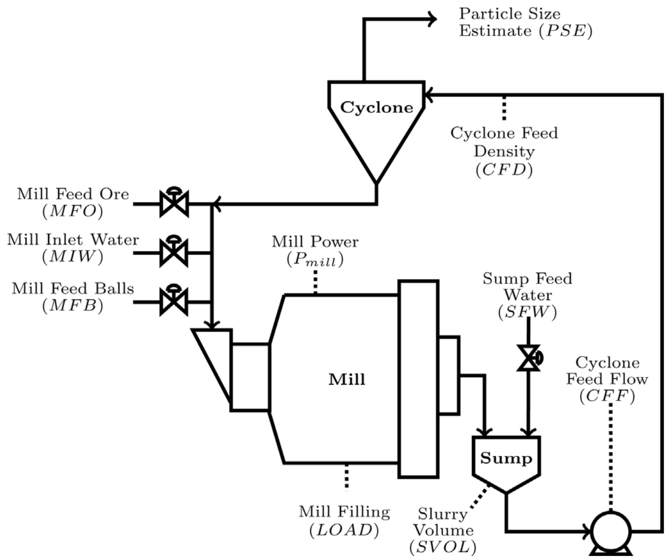

Fig. 1. Single-stage closed run-of-mine ore milling circuit.

Table 1
Manipulated, controlled and state variables.

Variable	Value	Unit
Manipulated variables		
CFF	374	[m^3/h]
MFO	65.2	[t/h]
SFW	140.5	[m^3/h]
MIW	4.64	[m^3/h]
MFB	5.68	[t/h]
Controlled variables		
PSE	67	[%<75 μm]
LOAD	33	[%]
SVOL	11.8	[m^3]
States		
X_{mw}	4.63	[m^3]
X_{ms}	4.65	[m^3]
X_{mf}	0.96	[m^3]
X_{mr}	1.99	[m^3]
X_{mb}	8.23	[m^3]
X_{sw}	8.10	[m^3]
X_{ss}	3.70	[m^3]
X_{sf}	0.76	[m^3]

proportional integral control (FOPI) [22], fractional order model reference adaptive control (FOMRAC) [23], and adaptive gain-order fractional order control [24]. Although the application of these fractional control techniques is found mainly in SISO processes [21,25], some were proposed for MIMO processes [26–29].

This work investigates the design and application of fractional order SISO controllers to a grinding mill circuit, which is a MIMO process. Thus, the control techniques preserve their simplicity in terms of SISO control, but are also capable of improving the robustness by means of the fractional operators in the presence of disturbances, parameter variations and noisy measurements. As far as the authors are aware, the use of fractional order controllers for grinding mill circuits has not been reported in literature, with the exception of the use of fractional disturbance observers [17] together with classic PI controllers.

Two fractional order SISO control strategies are proposed in this paper for a single-stage grinding mill circuit. The first control strategy, FOPI control, is a non-adaptive control strategy, and the second, FOPI control combined with FOMRAC, is an adaptive control strategy.

The paper is organized as follows: Section 2 describes the grinding mill circuit and the corresponding nonlinear model used for simulation; Section 3 introduces the design of the proposed SISO fractional controllers and Section 4 the tuning of the SISO fractional controller parameters; Section 5 introduces an LMPC, which is used to compare the behavior of the SISO fractional controllers; Section 6 presents the results obtained from simulations; Section 7 presents the conclusions.

2. Grinding mill circuit

2.1. Process description

A single-stage closed run-of-mine (ROM) ore milling circuit, as shown in Fig. 1, is considered in this study. The circuit consists of a semiautogenous (SAG) mill with an end-discharge grate, a sump and a hydrocyclone. The mill receives four streams as inputs: mined ore (*MFO*), water (*MIW*) to assist with material transport, steel balls (*MFB*) to assist with ore breakage, and underflow from the hydrocyclone.

The fraction of the mill filled with charge is denoted by *LOAD*. The ground ore in the mill mixes with water to form a slurry. The slurry is discharged from the mill into the sump through an end-discharge grate. The end-discharge grate limits the particle size of the discharged slurry. The slurry in the sump is diluted with water (*SFW*) and is pumped to the hydrocyclone for classification. The total volume of slurry in the sump is denoted by *SVOL*. It is assumed the pump is fitted with a variable speed motor to manipulate the cyclone feed flow-rate (*CFF*). The cyclone feed density can be adjusted by the sump dilution water as long as the sump does not overflow or run dry.

The hydrocyclone is responsible for the separation of the in-specification and out-of-specification ore discharged from the sump. The lighter, smaller and in-specification particles in the slurry pass to the overflow of the hydrocyclone, while the heavier, larger and out-of-specification particles pass to the underflow. The underflow is passed to the mill for further grinding while the overflow flows to a downstream process. The volumetric flow-rate of solids in the overflow is the throughput of the circuit and is equal to the volumetric feed rate of ore at steady-state operation of the circuit. The quality of the circuit product is indicated by the fraction of particles in the overflow smaller than specification size (*PSE*). The controlled and manipulated variables mentioned in this section are shown in Table 1.

2.2. Model description

The continuous time dynamic phenomenological nonlinear population balance model validated by Le Roux et al. [30] is used in this study to describe the circuit shown in Fig. 1. Each process unit in the circuit is modeled separately. The model is suitable for control purposes as it uses as few parameters and states as possible to produce reasonably accurate model responses.

The model divides the ore into three size classes: rocks, coarse ore and fine ore. Rocks are classified as ore too large to pass through the mill discharge grate. Coarse ore can pass through the mill discharge grate but is larger than the specification size. Fine ore also passes through the mill discharge grate but is within specification size. The sum of coarse and fine ore is defined as solids. Although only three size classes are used to describe the ore in the circuit, they are sufficient for the model to produce qualitatively accurate responses [31].

The model defines fives states to describe the mill charge volumetric hold-ups: water (X_{mw}), solids (X_{ms}), fines (X_{mf}), rocks (X_{mr}), and steel balls (X_{mb}). Because of the mill discharge grate, only three states are necessary to describe the sump slurry volumetric hold-ups: water (X_{sw}), solids (X_{ss}), and fines (X_{sf}).