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A Modular Dynamic Simulation Model for Comminution Circuits ⋆

B. Légaré * **J. Bouchard** ** **É. Poulin** ***

* LOOP, E4m, Department of Mining, Metallurgical and Materials
Engineering, Université Laval, Quebec City, Canada,
(e-mail: benjamin.legare.1@ ulaval.ca)
** LOOP, E4m, Department of Mining, Metallurgical and Materials
Engineering, Université Laval, Quebec City, Canada,
(e-mail: jocelyn.bouchard@gmn.ulaval.ca)
*** LOOP, E4m, Department of Electrical and Computer Engineering,
Université Laval, Quebec City, Canada,
(e-mail: eric.poulin@gel.ulaval.ca)

Abstract: Properly controlling comminution circuits is generally acknowledged to be highly profitable for any mining site's bottom line. On the other hand, the process control problem of comminution circuits is challenging due to circulating loads and non-linear transport/transformation rates. As the performance and robustness of the control system highly rely on a good understanding of the process dynamics, characterizing the deterministic behavior requires a certain level of operation disruption (bump tests). For a grinding circuit, it implies affecting the throughput and product size distributions. The management team can be reluctant to risk obvious consequences on downstream processing stages i.e. inadequate mineral liberation, reduction of product quality, and perhaps even recovery losses. Process simulation becomes in this case an attractive tool to design, assess, and pre-commission advanced control strategies. This paper presents a phenomenological dynamic simulator for comminution circuits developed in Matlab/Simulink®. The block model programming allows changing plant layout or control loops easily, and is flexible for future extensions or model upgrades as any block can be simply added to the library or replaced with its updated version. The flexibility of the modular approach allows testing any control system, from basic PID loops to advanced control schemes. A simulation case study shows how the simulation model can capture the behavior of an actual circuit once properly calibrated.

Keywords: Comminution, grinding, phenomenological models, dynamic simulation, process control.

1. INTRODUCTION

According to the estimations of Tromans (2008), comminution processes accounted for 29.3% of the total mining energy in the USA, which corresponded to 0.39% of the national energy consumption. For mining oriented countries like Canada and Australia, comminution represents respectively 1.86% and 1.48% of the total energy expenditure of the country. This mineral processing stage is essential for the extraction and recovery of most metals as the fragmentation liberates the ore from the valueless rock. The most widely used types of equipment are crushers and grinding mills. Considering that the relative efficiency of grinding mills ranges from 3 to 26 % (Tromans, 2008), great improvements and cost reductions can be achieved through a better overseeing of comminution operations. Among the various approaches put forward to tackle this issue, process control offers a well recognized potential, but faces difficulty to penetrate, partly because the benefits are difficult to predict prior to implementation. Moreover, developing a control system requires periods of time during which the circuit will be moved away from the nominal operating regime for model identification and commissioning purposes. The management team can be reluctant to risk the consequences on downstream processing stages, which can lead to punctual production losses. More than one design can also be on the drafting table, and not all of them can be tested in practice as they all involve important research and development costs. The use of dynamic simulation at the engineering stage of a control system, or to assess the impact of a change of operating or control strategy can certainly help mitigate some of these hurdles.

Comminution processes modeling is in constant evolution. Powell and Morrison (2007) reviewed the latest developments, ongoing work, and future trends. They concluded that the next generation of process models will be of a more fundamental type and usable for equipment design. Powell and McBride (2006) proposed a solution scheme to introduce breakage considerations into models based on discrete element methods (DEM). Despite these recent

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progresses, the particle balance model (PBM) approach is currently the most accepted and widely spread technique to simulate comminution processes.

The published simulators are basically of two types, either steady-state or dynamic. Examples of steady-state simulators are JKSimMet^{TM}, USIM PAC^{TM}, ModSim (King, 2012), and the one developed by Sosa-Blanco et al. (1999). These are appropriate for design purposes and circuit diagnosis. However, as they do not allow simulating transient states, they are inadequate to study the process variability.

Dynamic simulators are more appropriate to assess the impact of input variability and process control performances. Only two commercial mineral processing dynamic simulators are known to the authors: IDEAS^{TM} by Andritz Automation and HSC Sim© by Outotec Research. However, a lot of academic applications have been developed using Matlab/Simulink®. le Roux et al. (2013) proposed and validated a novel and simple non-linear model, Sbárbaro (2010), Liu and Spencer (2004), and Rajamani and Herbst (1991a) proposed more standard modeling approaches based on PBM as introduced by Epstein (1947).

The number of successful simulation examples of process control applications proved the relevance of dynamic simulator development. Rajamani and Herbst (1991b), Lestage et al. (2002), Duarte et al. (2002), Remes et al. (2010), and le Roux et al. (2013) all demonstrated how grinding circuit simulation can be used to develop advanced control strategies. Other focused their effort on controlling specific types of equipment. Salazar et al. (2014) and Steyn and Sandrock (2013) have developed model-based predictive controllers for semiautogenous mills and fully autogenous mills respectively, and Neesse et al. (2004) addressed the hydrocyclone control problem in a grinding circuit. All the above-mentioned studies may not have been possible without the use of dynamic simulators.

This paper presents an update to the modular dynamic simulation model for comminution circuits initially published by Sbárbaro (2010). The core of the paper is composed of Sections 2 and 3, which introduce the various models and block-programming simulation environment. Section 4 briefly discusses the issue of model parameter calibration and section 5 presents results of a simulation case study for an actual comminution circuit.

2. MODELS

2.1 Mill modelling

Mixing and transport. The multi-segment flow model schematized in Fig. 1, which is composed of a transport delay V_d followed by three continuously stirred reactors (CSTR) with internal classification, allows simulating both rod and ball mills.

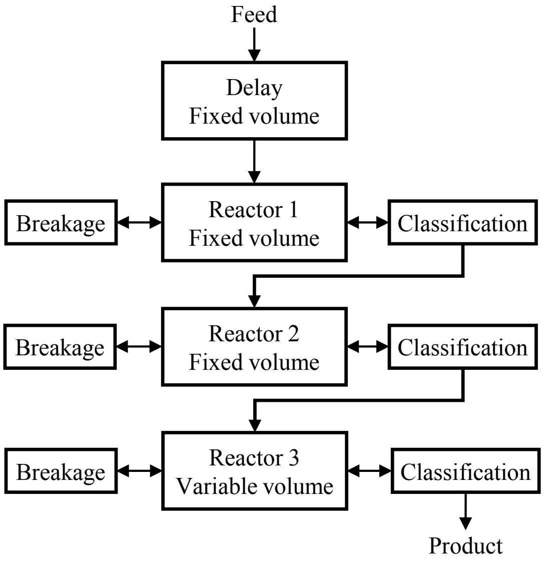

Fig. 1. Mill schematic flow model diagram

The first two CSTRs are identical. Their fixed volume V_f is expressed as a fraction of the grinding media interstitial volume. The last CSTR exhibits a variable volume V_v to account for dynamic fluctuations of the volumetric mill content. The volumetric discharge rate of the last CSTR D (m^3/h), corresponding to the mill discharge, is inspired by the Torricelli's theorem and thus proportional to the square root of the slurry volume V_v i.e.

$$D = \epsilon\Omega\sqrt{V_v} \tag{1}$$

where Ω $(m^{1.5}/h)$ represents a flow conductivity coefficient, and ϵ (le Roux et al., 2013), a unitless empirical rheology factor given by

$$\epsilon = \left(1 - s_v^{2.5}\right)\left(1 - \left(100^{(s_v-1)}\right)\right) \tag{2}$$

as a function of the slurry volumetric solids content s_v.

The original rheology factor proposed by le Roux et al. (2013) was modified here to avoid discontinuity and allow the slurry to flow even at high solids fractions.

Classification is an essential part of the flow model to predict a mill charge since particles of different sizes do not exhibit the same residence time. It also allows representing a higher solids fraction inside the mill than that of the feed and product as observed in practice. The classification function

$$C_i = \exp\left[-\kappa\left(\frac{X_i - X_{min}}{X_\kappa}\right)\right] \tag{3}$$

provides the probability of a particle to leave the reactor for each i^{th} size class. κ is the classification sharpness ranging from 0.5 to 3, and X_κ is the classification size parameter. Both are set according to operating conditions:

- internal CSTRs in ball mills: $X_\kappa = 40\%$ of top size ball diameter, and $\kappa = 0.5$;
- internal CSTRs in rod mills: $X_\kappa = P_{90}$ (sieve dimension larger than 90% of the particles) in the CSTRs, and $\kappa = 1.2$;
- grate discharge mills: X_κ must match the grate aperture, and $\kappa = 3$ at the mill discharge in the variable volume CSTRs.

Particles of the minimum size X_{min} are believed to flow with water without any restriction. The subtraction of X_{min} in the exponent numerator of (3) ensures that behavior.